RIGIDIFIED PNEUMATIC COMPOSITES

By

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The overall objective of the research presented in this dissertation was to address global issues of adequate housing for all and the need for more sustainable human settlement. In order to address these, the emerging technology of rigidified pneumatic composites was investigated. Rigidified pneumatic composites (RPC) are defined as thin flexible membrane structures that are pneumatically deployed. After deployment, these structures harden due to chemical or physical change of the membrane. Because of this change, these structures no longer require pneumatic pressure to maintain their shape. For the first time, a systematic listing of the various means available to develop polymeric materials useful in RPC technology is presented. With the aim to reduce the cost of RPC structures, a new material was proposed, developed, and evaluated. This material involved the formation of a semi-interpenetrating polymer network based on poly vinyl chloride

and an acrylate based reactive plasticizer. The economical and environmental performances of RPC structures using this new material were assessed by means of a case study. In this study, the performance of RPC technology was compared with that of a typical wood light frame structure in the application of a small single-family house. The study indicated that the cost of ownership in present day value for the RPC structure was approximately 35% less than the cost of a comparable wood light frame structure (foundation not included). The study also indicated that significant environmental benefits exist with the use of RPC structures. It was found that the RPC structure used significantly less resources compared to the wood light frame structure. About 3.5 times less materials coming from non-renewable fossil resources, about 2.5 times less material coming from trees, and about 19 times less materials coming from inorganic resources were used in the RPC structure relative to the wood light frame structure. The study concludes by delineating various means available to further increase the economical and environmental performance of RPC technology. Directions are provided to guide future developments of RPC technology.

CHAPTER 1
INTRODUCTION

Problem Statement

The twentieth century has witnessed some of the most extraordinary events in the history of mankind. Significant technological advances together with expanding knowledge in science has triggered vastly different patterns of social and economical development, especially in the Western world. These changed patterns cause serious problems including environmental degradation and depletion of traditional energy and material resources. In addition to these events, population has increased at an unprecedented rate. While wealth has increased continuously in the industrialized world, poverty and misery have continued to expand in the "less" developed world. Current population growth further aggravates and accelerates these unfavorable conditions.

It is widely agreed today that social, economic, and environmental aspects of human development are interrelated and require a comprehensive and global approach to improve them. In short, the objective of the international community today is to accomplish a sustainable world in which the social, economical, and environmental needs of present generations are accommodated without compromising the ability of future generations to meet their own needs (WCED, 1987). Accomplishing such sustainable development is currently at the center of many governmental, academic, and private research efforts. The construction industry, which is an important consumer of resources, but also provides significant opportunity for economic development, is at the center of this debate. So far, research efforts towards sustainable construction have

mostly resulted in the development of tools that can correctly assess the environmental or economic performance of competing construction systems. As a result of these efforts, numerous guidelines designed to promote sustainable practices in the construction industry have been established. Although such guidelines are very useful as a first step towards more sustainable construction practices, they do not per se trigger the development of new technologies. While nothing guarantees that sustainable construction can be accomplished with existing systems, innovation might be needed to increase the window of opportunity.

For many millennia, people have believed that the clues towards favorable development can be found by observing and applying the principles found in nature. This practice, which throughout the course of history has been given different names, is currently called "biomimetic" development. In light of sustainable development goals, this approach may prove to be very useful since biological systems have for long accomplished many of the sustainable goals currently aimed for. One technology emerging in this context of biomimetic development is pneumatic structures. It has long been argued that since pneumatic structures find firm examples in the biological world, they are economically and environmentally more sound than most conventional construction technologies. However, pneumatic structures have largely failed to deliver their promise. Main causes for failure are the limited durability of materials, high structural vulnerability, and the specific architectural expression that is associated with this technology. Because of these limitations, pneumatic structures find only a narrow niche of application today, most of which require the unique aspects of the technology. One such application can be found in the design of space structures. Reasons for this are obvious: pneumatic structures are very lightweight, very compact, and they pose little problem when deployed in space. Pneumatic structures are therefore a close to

ideal structural solution for space structure design. However, also in this application, the use of pneumatic structures is mainly limited to those applications that require only a short life span. The explanation is once more the issue of material durability, especially considering the high-energy radiation and particle impact encountered in a space environment. To solve this problem, a new technology has been developed that aims to take away current limitations. This technology consists of a process in which the membrane of a pneumatic structure rigidifies once inflated in the space environment. As a result, a rigid composite structure is obtained that does not need pressure to maintain its shape. Although issues of polymer durability remain to be addressed, such structures are much less prone to deflation by particle impact and are therefore a major improvement for long-term applications. The development of rigidified pneumatic composites (RPC) is also very promising for Earth based applications since this technology takes away the hassles previously encountered with simple inflatable structures. Further, the Earth environment is much less hostile in terms of radiation exposure than is the space environment: therefore polymer durability requirements are not as hard to accomplish. In addition, since rigid composite structures are developed, there exist more possibilities in architectural expression than previously possible. The combination of these improvements therefore may provide better chances of success than experienced with simple pneumatic structures. Upon investigation however, no simple transfer of this technology to earth based applications seems plausible. Explanations for this are manifold. First, materials developed for space application are very expensive because very strict conditions apply. Further, specific curing mechanisms developed for the space environment are inappropriate or even dangerous for use under normal conditions. So far, no systematic effort has been undertaken to identify more appropriate material solutions for use of this technology in Earth based

applications. Also, the potential economic or environmental benefits of this technology have not been assessed yet. The main purpose of this dissertation is therefore to address these two issues. First, a new material was developed to make application more affordable. Then, economical and environmental performance of this technology when used in a single-family house was assessed. Pneumatic structures have largely failed in the past because in their development some basic concepts of biological structures have been neglected. New approaches are therefore recommended to make these structures more efficient and in harmony with nature.

Purpose and Scope of Research

This research contributes to the development of construction technologies that address issues of adequate housing for all and the need for more sustainable human settlement. Although many areas for technological improvement exist, the focus of this dissertation was on addressing technological needs in the area of materials and methods of constructing buildings. A new construction system is proposed, developed, and evaluated. The scope of this evaluation was limited by assessing the performance of this newly developed construction system in the application of a single-family house. The objective was to obtain enough information to guide future technological development in this area of research.

Research Methodology

This dissertation starts with considering issues of global concern related to housing shortage, population increase, and sustainable development. Strategies developed by the international community to ease these problems are reviewed. The specific role that research in the areas of materials and methods of construction can play was extracted from these strategies. Biomimetics, a model for the development of sustainable technologies, is also reviewed. The technology of pneumatic structures served as an

example of biomimetic development. The evolution of this specific technology into the more advanced technology of Rigidified Pneumatic Composite (RPC) is also reviewed. A theoretical framework is provided that can guide the development of new material solutions. Proof of concept of one such solution is provided by means of experiment. Samples were prepared and material properties determined. The economical and environmental performances of this material were assessed by considering its application in a single family house. Conclusions were drawn from these results and used to recommend actions for further research in this area. Methods that apply to each step of the research will be provided in the relevant chapters.

Research Objectives

The research objectives of this dissertation are the following:

1) Establish a theoretical framework that can be used to develop material solutions that are relevant to the development of rigidified pneumatic composites.

2) Establish, by means of experiment, the validity, feasibility, and mechanical performance of one promising material solution.

3) Quantify the economical and environmental performances of the developed system in the application of a single-family house.

4) Evaluate technology performance and identify areas for improvement and further research.

Research Sequence

Step1: Theoretical Solutions

This part of the research involved an analysis of required material functions and relating these functions to physical and chemical attributes of materials. From this, theoretical models were developed that could be used to develop a specific material. This information was mainly obtained by means of a literature review.

Step 2: Experimental Work

A promising approach was selected from the theoretical models established in step 1. A more detailed review of the literature was performed to determine optimum material composition. Material samples were prepared to verify system feasibility. After this, some mechanical and physical properties of the material were determined.

Step 3: Assessing Economic and Environmental Performance

The objective of this part of the research was to assess the economic and environmental performance of rigidified pneumatic composites in the application of a single-family house. To accomplish this objective, the performance of the new system was compared with the performance of a more conventional system that served as a standard "base case". The building design selected for basis of comparison was a small rectangular single-story house with overall dimensions of 24 by 48 feet, with an 8-foot high ceiling.

Step 4: Results and Discussion

A synopsis of research findings was presented including a summary of research results. Economical and environmental performances of the technology were evaluated by comparing major material and economic costs of the system. From this, areas for system improvement and further research were identified.

Contribution

This research systematically presents, for the first time, a listing of the various means available to develop polymeric materials useful in Rigidified Pneumatic Composite technology. In addition, a new material was developed and tested that could possibly reduce the cost of RPC structures significantly. Economical and environmental performances of RPC technology were assessed by means of a case study. In this

study, the performance of RPC technology was compared with that of a typical wood light-frame structure in the application of a small-scale single-family house.

CHAPTER 2
RESEARCH BACKGROUND

The development and evaluation of new construction technologies that addresses issues of housing shortage, and the need for more sustainable human settlement are the purpose of the research presented in this dissertation. This chapter will first discuss issues of global concern related to population growth, housing shortage, and the environment. It will further present some of the strategies developed by the international community to accomplish adequate housing for all and sustainable human settlements. The specific role that architectural research in the areas of materials and methods of construction can play to ease these global concerns will be extracted from these strategies. The role of biomimetics as a model for developing favourable technological development will be clarified. A brief review of some biological concepts will also be provided. This chapter will conclude with introducing major developments in the area of pneumatic structures.

Issues of Global Concern

Population Growth

The twentieth century has witnessed extraordinary population growth; world population increased from 1.65 billion to 6 billion [United Nations, The World at six billion]. It is further projected that population will continue to experience significant increase during the twenty-first century. According to the United Nations population division, world population will reach between 7 and 10 billion by the year 2050 [United Nations, Long range world population projections, 2000]. The explanation for these

events are manifold; the ability to expand into new habitats and climate zones, and the ability to increase the carrying capacity of existing habitats, are among the major explanations for ancient population growths [Starr and Taggart, 1995]. Further, by bringing many disease agents under control and by tapping into concentrated, existing stores of energy, humans have continued to side-step certain factors that had previously limited their population growth. Revolutions in agriculture, science, and industry, together with health care improvements are the main events that have allowed us to sustain the extraordinary population increase of the past 200 years. Figure 2.1 links major technological improvements to population increases. Sustained population growth is, besides technological and cultural determinants, also related to economic development. Population growth rates tend to decrease when economic welfare increases. Examples of this phenomena can be observed in Western Europe and other industrialised regions of the world where population growth has stagnated or declined with increasing economic development [Starr and Taggart, 1995]. This phenomena forms the basis of the demographic transition model that correlates population growth to the different stages of economic development (Figure 2.2). The demographic transition model also explains why major population growth continues to occur in economically less developed countries. For example, the average world population growth rate for the period from 1995 to 2000 was 1.3%. However, the growth rate was 1.6% and 0.3% for less developed and more developed regions respectively [United Nations, Long range world population projections]. This confirms the trends predicted by the demographic transition model.

Adequate Housing

Together with rapid population growth, the twentieth century has experienced an increase in the number of people being homeless or living under inadequate housing

conditions. Although the percentage of people living in such conditions has declined, their absolute numbers has increased owing to rapid population growth, especially in the developing countries. In addition, a continued migration from rural to urban regions exists increasing the number of people living in cities. It is estimated that today more than three billion people, one half of the world's population, live in urban regions. According to the UN, half of this urban population today still lives in slums of some kind, one hundred million are utterly homeless, and between thirty and fifty percent of city dwellers in developing countries lack access to basic drinking water and sanitation facilities. In addition, it is predicted that the level of urbanization will further increase reaching 80% for more developed regions and 49 % for less developed regions by the year 2015 [United Nations: World Urbanization Prospects, the 1999 revision].

Sustainable Development

The earth's resources, natural systems, and human population are inherently connected. While the impact on the environment of an estimated 100 million people was negligible 3000 years ago, the combined impact of 6 billion people living today is much more profound. Unprecedented population growth has increased the concern about the Earth's carrying capacity and triggered the debate concerning sustainable development. In 1987, the World Commission on Environment and Development defined sustainable development as comprising those activities that meet the needs of the present without compromising the ability of future generations to meet their own needs [WCED, 1987]. The effects that current population has on the environment are manifold and full description is beyond the scope of this study. Instead, a few indicators will be given that describe the specific impact of the construction sector. The construction industry is a major consumer of natural resources and energy. According to a study performed by the Worldwatch Institute, one-tenth of the global economy is devoted to construction and

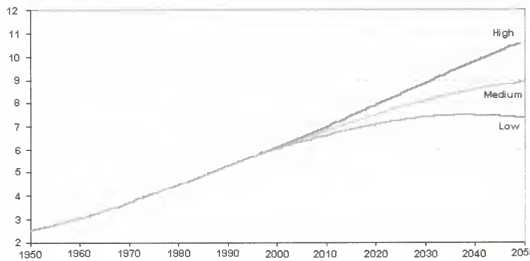


Figure 2.1 World population size in billions: past estimates and medium-, high- and low fertility variants, 1950-2050 (*Source*: United Nations Population Division, *World Population Prospects: The 1998 Revision*, forthcoming)

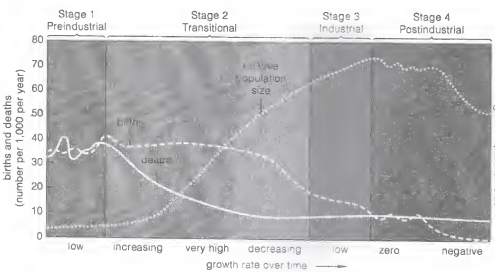


Figure 2.2 Demographic Transition Model for Western Europe (Source: Starr and Taggart, 1995) (dotted line: relative population size, dashed line: births, solid line: deaths)

one-sixth to one-half of the world's major resources are consumed by construction and related industries. Also, fiftyfive percent of the wood cut for non-fuel uses is for construction and forty percent of the world's materials and energy is used by buildings [Roodmann and Lenssen, 1995].

International Strategies

United Nations and International Co-operation

Present problems of population growth, inadequate housing, and environmental degradation are interrelated exceeding boundaries between countries and continents. Hence the hope for any solution can only be found through international agreement and co-operation. Accomplishing this goal is one of the main objectives of the United Nations. Established on 24 October 1945, the UN has four purposes: 1) maintain international peace and security, 2) develop friendly relations among nations, 3) co operate in solving international problems and in promoting respect for human rights, and 4) be a centre for harmonising the actions of nations [Charter of the United Nations, Chapter 1, article 1]. On December 10, 1948, the General Assembly of the United Nations adopted the Universal Declaration of Human Rights. According to article 25 of the Universal Declaration of Human Rights:

> Everyone has the right to a standard of living adequate for the health and well-being of himself and his family, including food, clothing, housing and medical care and necessary social services, and the right to security in the event of unemployment, sickness, disability, widowhood, old age or other lack of livelihood in circumstances beyond his control. [Universal Declaration of Human Rights: article 25-1, adopted by the General Assembly of the United Nations on December 10, 1948]

Adequate housing hence is one of the basic human rights to be accomplished. Therefore, according to the UN mission, co-operation to solve this international problem of housing shortage is needed in order to promote respect for human rights.

Evolution of Strategies

Many initiatives have been undertaken since the UN's adoption of the Universal Declaration of Human Rights and a gradual change in strategy can be observed. According to a recent report: "The whole framework for thinking about development and policy has changed in important ways. Centralised planning, top-down blueprints, and emphasis on filling deficits in capital, skills and technology have given way to market and people-based solutions, process approaches, and an emphasis on building capacity and institutions to manage change" [UNCHS, 1998]. In other words, the belief that we can superimpose solutions on less fortunate people regardless of their beliefs, culture, specific environments, and technical skills becomes less acceptable. For example, many building projects in the past have adapted technologies that were developed in the context of more developed countries. Technologies used depended on imported plant, materials and equipment as well as foreign professionals and contractors, and hence were often not sustainable given the local context. There are currently two main documents that address the issues of sustainable development and human settlement in a global context. These are Agenda 21 and the Habitat Agenda.

Earth Summit, Agenda 21

In 1992, The United Nations hosted a landmark Conference on Environment and Development in Rio de Janeiro, Brazil. The assembled leaders of more than 100 countries adopted Agenda 21, a global plan of action to accomplish sustainable development in the 21st century. Agenda 21 addresses a vast array of subjects related to sustainable development goals, it also reaffirms the right to adequate housing as a basic human right as enshrined in the Universal Declaration of Human Rights [Agenda 21: Chapter 7, item 7.6]. Agenda 21 further provides specific guidelines to promote sustainable human settlement development. Major programme areas include the

"provision of adequate shelter for all" and the *"promotion of sustainable activities for the construction industry"*. In order to accomplish affordable housing for all, Agenda 21 stipulates that the objective is to achieve adequate shelter for rapidly growing populations and for the currently deprived urban and rural poor through an enabling approach to shelter development and improvement that is environmentally sound" [Agenda 21: Chapter 7, item 7.8]. In order to promote sustainable activities for the construction industry, Agenda 21 stipulates that:

> The objectives are, first, to adopt policies and technologies and to exchange information on them in order to enable the construction sector to meet human settlement development goals, while avoiding harmful side-effects on human health and on the biosphere, and, second, to enhance the employment-generation capacity of the construction sector. Governments should work in close collaboration with the private sector in achieving these objectives. [Agenda 21: Chapter 7, item 7.68]

Specific activities aimed to promote sustainable construction industry activities include the following:

> • Establish and strengthen indigenous building materials industry, based, as much as possible, on inputs of locally available natural resources.
> • Formulate programmes to enhance the utilisation of local materials by the construction sector by expanding technical support and incentive schemes for increasing the capabilities and economic viability of small-scale and informal operatives which make use of these materials and traditional construction techniques.
> • Adopt standards and other regulatory measures which promote the increased use of energy-efficient designs and technologies and sustainable utilisation of natural resources in an economically and environmentally appropriate way.
> • Formulate appropriate land-use policies and introduce planning regulations specially aimed at the protection of eco-sensitive zones against physical disruption by construction and construction-related activities.
> • Promote the use of labour-intensive construction and maintenance technologies which generate employment in the construction sector for the underemployed labour force found in most large cities, while at the same time promoting the development of skills in the construction sector.

> • Develop policies and practices to reach the informal sector and self-help housing builders by adopting measures to increase the affordability of building materials on the part of the urban and rural poor, through, inter alia, credit schemes and bulk procurement of building materials for sale to small-scale builders and communities. [Agenda 21: Chapter 7, item 7.69]

Habitat II, The Habitat Agenda

To address the complex set of issues related to human settlement, the UN has created the *"united nations centre for human settlement"* (UNCHS or Habitat). During its latest conference, the UN Habitat II conference held in Istanbul (Habitat II, 1996) the international community committed itself to achieve two principal goals: *"Adequate shelter for all"* and *"Sustainable human settlement development in an urbanising world"*. The means to accomplish these two objectives are outlined in the "Habitat II Agenda", currently the main document used by the UN to guide future actions in this area. In essence, the Habitat Agenda reaffirms and elaborates on commitments made in Agenda 21 concerning *"Adequate shelter for all"* and *"Sustainable human settlement "* [The Habitat Agenda: Chapter 1, item 6]. The UN strategy continues to be directed towards the development and implementation of enabling policies rather than on direct provision [The Habitat Agenda: Chapter 1, item 3]. This enabling approach leaves the final decision on how people should house themselves to the people involved. Governments should withdraw from direct provision and instead provide a supportive legal, financial and regulatory framework that enable markets to operate efficiently. Recommendations to develop such policies are outlined within the global plan of action contained within the habitat agenda. Although the enabling approach is central, the Habitat Agenda does certainly not exclude the development of new technologies. Many recommendations that specifically direct the development of new technologies in the area of materials and

methods of construction are described within the plan of action of the Habitat Agenda. Some of the most relevant guidelines include:

- Encourage the development of environmentally sound and affordable construction methods and the production and distribution of building materials, including strengthening the local building materials industry, based as far as possible on locally available resources [The Habitat Agenda: Section IV B-2, item 70]
- Promote self-built housing within the context of a comprehensive land-use policy [The Habitat Agenda: Section IV B-3, item 74]
- Strengthen the capacity of both the public and private sectors for infrastructure delivery through cost-effective, employment-intensive methods, where appropriate, thereby optimising the impact on the creation of employment information [The Habitat Agenda: Section IV B-3, item 91]
- Where appropriate, encourage and support the establishment and expansion of environmentally sound, small-scale, local building materials industries and the expansion of their production and commercialisation through, fiscal incentives and the provision of credit, research and development, and information [The Habitat Agenda: Section IV B-3, item 91]
- Intensify and support research efforts to find substitutes for or optimise the use of non-renewable resources and to reduce their polluting effects, paying special attention to recycling, reuse of waste materials and increased reforestation [The Habitat Agenda: Section IV B-3, item 92]
- Encourage and promote the application of low-energy, environmentally sound and safe manufacturing technologies backed by appropriate norms and effective regulatory measures [The Habitat Agenda: Section IV B-3, item 92]
- Encourage the use of safe industrial and agricultural waste products and other types of low-energy and recycled building materials in construction [The Habitat Agenda: Section IV C-6, 146]

Biomimetics, a Model for Developing Sustainable Technologies

Biomimetics, a Brief Introduction

There currently exist significant interest to study biological development as model for human development. Since ancient times nature has served as source of inspiration for many of the human aspirations and activities in science and engineering. Historically, analogies between biology and architecture have always been present. Such analogies have ranged from proportional and geometrical studies like those conducted by

Vitruvius, the study of anatomy as conducted by DaVinci and others, romantic interpretation as practised by for example Sullivan, and theories on form and adaptation as proclaimed by for example LeCorbusier and Ozenfant. To list a few classical statements, Horatio Greenough, an American sculptor and aesthetician, proclaims an examination of biological structures as source for inspiration and education (Horatio Greenough, 1864). In one passage he states that:

> If, as the first step in our search after the great principles of construction, we but observe the skeletons and skins of animals, through all the varieties of beast and bird, of fish and insect, are we not as forcible struck by their variety as by their beauty? There is no arbitrary law of proportion, no unbending model of form. There is scarce a part of the animal organisation which we do not find elongated or shortened, increased, diminished, or suppressed, as the wants of the genus or species dictates, as their exposure or work may require..... It is neither the presence nor the absence of this or that part or shape or color that wins our eye in natural objects; it is the consistency and harmony of the parts juxtaposed, the subordination of details to masses, and of masses to the whole. The law of adaption is the fundamental law of nature in all structures." [Quoted in Gifford, 1966, page 145]

Another classic work is provided by D'Arcy Wentworth Thompson in his book "On Growth and Form" in which for example a comperative anatomy of bridges is provided [D'Arcy Wentworth Thompson, 1912]. In the late 1920s and 1930s, the concept of 'biotechnic' or ' biotechnics' continued in this tradition. The essence of this proposal was that in the evolution of plants and animals, nature herself had already made a great variety of inventions, embodied in the designs of organs or in the adaptations of the limbs. These inventions solved in ingenious ways all kinds of functional and engineering problems. It only required a diligent study of the engineering of nature, and man would find there the solution to all his technical needs; natural models requiring only to be copied in the design of machines or structures. In this way, instead of technological evolution needing to be highly time-consuming, it would borrow the time already

invested in the organic evolution of these natural counterparts to human artefacts [Steadman, 1979]. Biotechnic received the more popular name "bionics" in the 1960s, in essence however the scope and objectives remain the same [Gerardin, 1968]. One of the current names for "biotechnics" or "bionics" is the term "biomimetic" which has a primary aim to mimic biological principles. The term "biomimetic" was likely coined by Breslow and was used to describe his study of natural enzymes as a model to develop artificial enzymes [Breslow, 1986]. Biomimetic, means to imitate or mimic some specific biological function, usually without the need of utilizing living systems [Gebelein, 1990].

Current Directions in Biomimetic Research

Major scientific theories that are common knowledge today still needed to be established during 19th and early 20th century. Observation was largely limited to what one could perceive with the naked eye or at most a light microscope. Biological processes were not well known and more full explanation was still awaited for. 19th and early 20th century architecture largely resulted in mimicry of biological form and structure rather than mimicry of function or process as currently aimed for in biomimetic research. The past century is unique in that scientific endeavour has resulted in a far more detailed knowledge of biological systems, processes, and materials. The availability of more refined tools has increased our level of conception of living matter and the nature of its processes. Current biomimetic research involves the study of molecular architectures as related to physical performance and biological function. As stated before, the term "biomimetics" finds its origins in the study of folded proteins and mimicking their related enzymatic functions synthetically. During the past decades, an increased interest has occurred to extend the biomimetic approach to the study of biological support systems. The study of biological composite material, as guide to develop new synthetic materials and composites, has become more commonplace

today [Tirrell, 1994]. More recently, the development of so-called "smart materials" has extended the biomimetic approach further into the exploration of interactive materials and structures as they can be found in nature. The translation of these findings into the realm of architecture still largely remains to be established. No clear aesthetic motivation is to be expected, hence the discussion will rather be one of economical and environmental advantage.

Biological Structures, a Closer Look

Biological Materials

Living organisms are composed of only a few atomic elements, principally carbon, hydrogen, oxygen, and nitrogen, in smaller amounts a few other elements are also used [Mathews & van Holde, 1990]. Together these elements form the molecules necessary to make life happen. Nature is very consistent in the types of molecules it forms from these atoms. Metabolic processes transform water, carbon dioxide, and ammonia into nucleic acids, proteins, carbohydrates, and lipids. One explanation for this rather limited pallet of atoms incorporated into earth's living organism is the consideration of bond energies. Since living organisms require both stability and change, the bonding between atoms in bio-molecules must both be sufficiently strong to ensure structural stability but also not be so strong as to prevent any reactions. Bonds in bio-molecules are therefore strong enough to maintain themselves under normal environmental conditions, but not so strong as to prevent catalytic reactions necessary to life. Considerations of bond energies explains why abundant elements like silicon are not found in most biological life forms. The energy required to form silicon-silicon or silicon-oxygen bonds is much higher than the energy needed to form for example a carbon-carbon bond. The selection of biological building components is thus directly related to the energy needed to make and maintain large structures. Energy availability in turn is determined by the prevailing

environmental conditions of pressure and temperature on Earth [Mathews & van Holde, 1990]. Further, most materials used in biological structures are composite in nature. A particular function is accomplished by composition of a number of different materials. The basic structural materials to assemble these are the proteins and carbohydrates (rigid structures), and lipids (cell membranes). Nature has the ability to use these basic building materials in stunningly different ways. A committee established by the national research council made following observation regarding the recurring characteristics of biological materials [Tirrell, 1994].

- Recurrent use of molecular constituents such that widely variable properties are attained from apparently similar elementary units.
- Controlled orientation of structural elements
- Durable interfaces between hard and soft materials
- Sensitivity to and critical dependence on the presence of water
- Properties that vary in response to performance requirements
- Fatigue resistant and resiliency
- Controlled and often complex shapes
- Capacity of self-repair

To illustrate the stunningly different ways nature uses the same material, collagen is used as crimped fibers in tendons to absorb, store, and transmit energy between muscle and bone. Collagen is also used in the junctions between high and low modulus materials in articular cartilage. And further, collagen is used as a component in hard materials such as bone [Tirrell, 1994]. Another illustration is the importance of orientation as a defining factor in the mechanical properties of biomaterials. A typical example is the controlled orientation at different levels of organization we find in the structure of wood. First, wood cells are mainly aligned along the axis of a tree. Further, each cell wall is composed of thin laminates each being composed of high modulus cellulose fibers embedded in a soft lignin matrix. Predominant fiber orientation in each

lamina differs so as to accomplish uniform properties throughout the cell wall. Toughness is accomplished by such mechanisms as fiber pull out and diversion of propagating cracks around individual cells [Tirrell, 1994].

Biological Design

Biological structures can only operate successfully if their design is fit to the environment in which they operate. The opposite is also correct, biological structures can survive only if they inhabit environments fit to their design. Essential for survival is thus to accomplish synergy between design and environment. A specific environment results in specific stresses such as temperature, pressure, radiation, chemical and predatory attack. Stress response can differ significantly among species, both active and passive defence mechanisms occur. Land snails for example protect their weak body from predators by means of a passive rigid shell. Humans on the other hand protect themselves from predators by means of much more active defense mechanisms. Many of the constituents of biological structures are extremely prone to environmental damage. Most biopolymers degrade readily upon exposure to UV light. As discussed earlier, this results from particular molecular bond strengths necessarily selected to make life possible at prevailing environmental conditions. Passive response mechanism can shield weaker components from the effects of UV radiation. Very few invertebrate organisms exist for example that are not contained within a protective envelope when found in an environment where they are exposed to UV light. On the other hand, invertebrates found in an aqueous environment, where exposure to UV light poses less a problem, are not necessarily contained within such a shielding envelope, examples are jellyfish and sea-wasp.

Developments in Pneumatic Structures

Pneumatic Structures

"Pneumatic structures can be defined as a system in which a layer stressed in tension envelops a filling, the filling makes the skin become the bearing structure of the pneumatic device" [Bubner, 1975]. Pneumatic structures have both tensile and compressive bodies that act upon each other. For pneumatic structures in general, the tensile body is composed of the external skin while the compressive body (filling) can be a gas, liquid, or solid that is contained within and presses against this external skin. In the case of inflatable structures, the compressive body is the internal pressurized gas, usually air. Examples of pneumatic systems that use a liquid compressive core can be found in cellular organisms. Examples of pneumatics with solid cores are sand-bag structures, and foam-inflated structures. Pneumatic devices have been known since ancient times in the form of wine-bags, sails, inflatable beds, and many other applications [Dent, 1972]. The concept of pneumatic devices becomes clear when the first hot air balloon was made. By far the most extensive application of pneumatic devices today can be found in the form of the pneumatic tire. The term *pneumatic* is therefore preferred over *inflatable* since it describes a more generic type of structure. The first recorded proposition of using a pneumatic device for making a building comes from F.W. Lanchester when he filed for a patent on this concept in 1917. Envisioned applications included military hospitals and very large spatial enclosures [Quarmby, 1974]. For many years, pneumatic structures proposed to enclose space were considered to be a structural curiosity rather than a practical solution. [New interest emerged during the Second World War, where applications included: inflatable boats, gas filled balloons, and also dummy inflated structures to deceive the enemy.] After the war, Walter Bird first started using pneumatic structures for radome protection followed

by a range of other non-military applications [Dent, 1972]. The first consistent study on pneumatic structures was probably undertaken by Frei Otto and the Institute for Lightweight Structures which he founded at the University of Stuttgart. Frei Otto's work and interest mainly consisted of the study of tensile structures, also including pneumatic structures. His first major publication on the topic, "Tensile Structures", provides a detailed overview of types of pneumatic devices including design options and case studies. This work also provides an introduction to form finding techniques and structural analysis of some common pneumatic forms [Otto, 1967]. An interesting shift occurred in his work when he also started to develop a keen interest in biological structures. In co-operation with the Institute for Lightweight Structures, numerous articles were published between the 1960's and the late 1980's. These publications cover a multitude of topics including animal structures, pneumatic structures in nature, liquid films and bubbles, and many more (IL-series: 1 through 40). Except the work of Frei Otto, little organized effort has been made to study pneumatic structures.

Pneumatic Formwork

Pneumatic devices have the capability to support very heavy loads while only under moderate internal pressure. Pneumatic tires are perhaps a good illustration of this. The ability to support heavy loads can also be used to support wet concrete or other substances that become structural upon hardening. In this technology, the inflatable form is used as a temporary form to shape the final structural substance (for example concrete). The first use of such pneumatic formwork occurred in Italy in 1936 when tubular inflatable formwork was used to construct underground waterlines out of concrete [Sobek, 1991].

Concrete

A variety of different systems to construct concrete shells have been developed. An overview of this technology is provided by Sobek [Sobek, 1991]. One system, called the binishell, was invented by Dante N. Bini in Italy. A flat membrane attached to a tension ring sitting on the ground is used. Steel reinforcement is distributed on the membrane after which wet concrete is poured on top of the not yet inflated membrane. Once the concrete is spread over the membrane, the membrane is inflated causing it to lift up the concrete into its desired shell configuration (figure 2.3). After hardening, one is left with a solid concrete shell. After this, the pneumatic form can be removed. The first concrete shell that applied this technology was erected in 1965 in Bologna Italy by Dante N. Bini, the dome spanned 12 meters. One year later, a 30 meter dome was constructed using the same technology. Various modifications occurred afterwards, all of which aimed for better surface control or to reduce the amount of concrete needed. Domes spanning over 100 meters are now possible to build using this technology [Bini, 1974].

Phase 1: Placing reinforcement + Pouring Concrete on top of membrane

Phase 2: Inflation and concrete hardening

Figure 2.3 Bini Shell

Shotcrete

Another method applies a slightly different sequence. First, a membrane with shape of the proposed final shell is properly attached to a support system sitting on the ground. After inflation, steel reinforcement is placed upon the inflated membrane. The final step involves applying "shotcrete" to the membrane (figure 2.4). [Sobek, 1991].

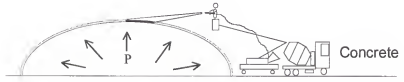


Figure 2.4 Shot-Crete

Pre Cast

Systems that make use of precast concrete panels are also developed [Bini et al., 1992]. In this system, precast panels are placed on top of a flat membrane. After inflation, the spaces in-between panels are filled with concrete. After hardening of this concrete, all precast elements become attached producing a supporting shell (figure 2.5).

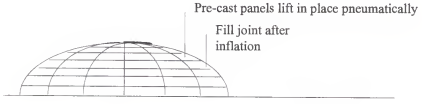


Figure 2.5 Pre-Cast

In-Situ Foam

The concept described above can also be applied with materials other than concrete. The Bayer Chemical Corporation developed a system in which a polyurethane foam is sprayed on top of an inflated membrane (figure 2.6). Several hundred emergency shelters were built in Turkey and Peru using this technology [Dent, 1972]. Various other foams and hybrid material can also be used. Dow Chemical developed the styrodome concept, a system very similar to the Bayer concept, only no pneumatic form was needed [Quarmby, 1974].

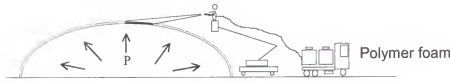


Figure 2.6 In-situ foam

Water/Ice

Experimental systems that use ice as supporting material for construction of a dome were also developed. In these, liquid water is sprayed on top of an inflated form at sub-zero conditions. Ones the water comes in contact with the form it starts to transform into ice (figure 2.7). If sufficient layers are applied, a rigid shell made from ice is obtained. Envisioned applications include the construction of temporary structures in very cold climates and the construction of radiation barriers for space structures [Glockner, 1977].

Figure 2.7 water/Ice

Polymer Resin Infusion

Increasing legislation to limit styrene emission (mainly from polyester resin systems) into the workplace has been a key factor in promoting the development of new manufacturing techniques. One of these techniques involves a closed molding technique that applies a flexible polymeric film on top of a solid mold. Resin is infused in-between the solid mould and the flexible film preventing styrene from entering the workspace [Williams et al. 1996]. This concept was further expanded by replacing the solid mould with a second polymeric film. Resin was infused in-between two polymeric films, the flexible mold was given the desired shape pneumatically (figure 2.8).

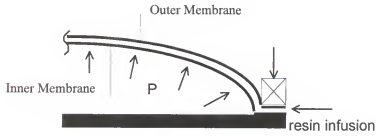


Figure 2.8 Polymer resin infusion

Rigidified Pneumatic Composites

Considerable interest in pneumatic structures for architectural application existed during the 1950's to 1970's. Today, significant interest in pneumatic structures continues to exist among those involved with the design of space structures. For space applications, pneumatic structures have many advantages compared to conventional construction technologies. They are lightweight, have compact transportation volume, and are easy to deploy in space. However they also have some distinct disadvantages such as high vulnerability, and limited durability. High vulnerability and severe space conditions have limited the use of pneumatic structures to those applications where no long service life was required. In an effort to increase the long-term performance of inflatable structures, the "Rigidified Pneumatic Composite" concept (RPC) was developed [Dent, 1972]. In general, RPC consists of a membrane envelope that can be inflated in space. After inflation, due to chemical or physical change, the inflated membrane stiffens. As a result, these structures become self-supporting and do not need a constant gas supply to maintain shape. When penetrated by space particles, the original gas will escape, but the structure will maintain shape and can therefore continue to function.

RPC Material Requirements

The basic requirement for a material to be useful in RPC technology is to accomplish a certain increase in the modulus of elasticity at a distinct point in time (figure 2.9). The amount of increase that is needed is a function of structural design and loads. Besides accomplishing an increase in modulus of elasticity, it is of equal importance to have precise control over the time when this change in modulus of elasticity will occur. In general therefore, research on RPC technology focuses on three major areas; 1) development or identification of membrane materials that can stiffen under space

conditions, 2) obtain exact time-control on this stiffening process, 3) structural analysis of inflatable structures before and after rigidification (stress analysis, surface control, thermal effects, etc.). So far, research on RPC technology is largely scattered over periods of time and location. The few reports that are published are mostly the result of a particular project that required some investigation of RPC technology.

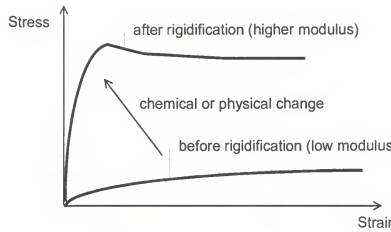


Figure 2.9, RPC material change

RPC Systems

Pre-preg membranes (thermal, UV, or reactive gas cure)

These systems make use of thermosetting polymer-matrix systems that are partly cured (B-staged) and contain fiber fabrics for reinforcement. Because of this partial cure, the resin obtains a certain viscosity and can function as membrane. Although not specifically developed for RPC technology, pre-preg membranes can also be used to construct inflatable structures. The basic material requirements are storability, flexibility, ability to cure, and ability to withstand space conditions before and after cure. For

reinforcement, the basic selection criteria are specific strength and modulus of elasticity [Lodgard, 1988]. The first use of pre-preg material in RPC technology occurred in the 1956 ECHO satellites. Some of the first communication satellites launched by NASA consisted out of simple space inflatable spheres made from Mylar film [Dent, 1972]. These structures where extremely prone to penetration by space debris causing constant leakage of gas. Because of this leakage, a continuous gas supply was needed to maintain shape. The next generation of ECHO communication satellites therefore applied a resin pre-impregnated textile membrane that could also be inflated in space. After inflation, the resin solidified by the radiant heat provided by the sun. After cure, a thin walled rigid fiber reinforced polymeric composite sphere was formed that could be used to reflect radio waves. After solidification these structures were less affected by penetration, no internal gas pressure or gas supply was needed to maintain shape. In light of RPC technology development, the use of pre-pregs is still the most prevailing technology. In a project currently under development by NASA, pre-preg materials are used to construct an experimental antenna to be deployed in space [Codogan, 1998]. Besides the use of more advanced resin systems (relative to those available in1956), the only difference is the use of electrical power (provided by the space-shuttle) to heat-cure the pre-preg by means of electrical resistance-wires embedded in the membrane. The use of pre-preg material is a typical engineering solution to the problem of RPC technology in that an existent technology is modified towards a specific problem. The use of pre-preg material however has some limitations. For example, pre-preg materials have limited shelf-live and usually require storage at low temperatures. For space applications, short shelf-live (< 1 year) limits application to projects that can be accomplished in a relative short period of time (an Earth satellite). Longer-term space missions (mission to Mars) are not yet possible since materials would become spoiled

upon arrival. Further, it is very difficult to accomplish full thermal cure of pre-preg material under space conditions, especially when the sun is the only available source of thermal energy. Typical curing time for rigidification is 3 hours at 120 °C [Lodgard, 1988]. Structures need to be rotated in such a way that full thermal cure of all parts can be accomplished in a reasonable period of time. Designs are therefore limited to relative simple configurations. Thicker or more complex three-dimensional membranes are not yet possible because of this. Although the use of other energy sources is an option, they tend to take away some of the simplicity of the system. In a review by Bernasconi, the use of hot gas to accomplish thermal cure was further proven not to be a feasible approach [Bernasconi, 1995]. Approaches suggested to overcome problems of thermal cure include the use of chemical catalyst such as (highly toxic) boron trifluoride gas to speed up the thermal curing reaction [Bernasconi, 1990]. In this approach, the structure is inflated with the catalytic gas (or a mixture of gasses), after inflation the gas diffuses into the membrane enhancing the normal thermal cure of the membrane. Cure through UV-light is also possible, but similar limitations to heat cure apply. Membranes can not be very thick since the penetration depth of UV light into solid substance is limited. Uniform exposure is also needed posing the same limitation on design configuration. Although in addition to these approaches, others may have been developed, but for proprietary reasons, results are not yet published.

Strain Hardening

This approach relies on the ability of certain materials to harden upon strain beyond the elastic limit, materials proposed are the use of aluminum foil [Cadogan, 1998]. In this approach, thin aluminum foil is used to construct an inflatable structure. Once brought into the space environment, the foil membrane is inflated and the material is strained beyond the elastic limit and plastic regime until it reaches the strain hardening regime.

Once the material is hardened upon strain, inflation pressure can be released and the structure will remain its shape (figure 2.10).

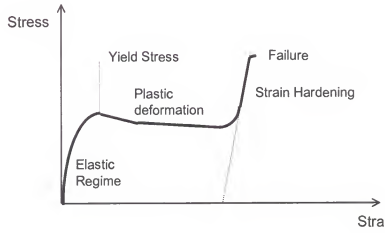


Figure 2.10 Strain hardening

The approach of strain hardening is very simple since it does not rely on chemical cure. Also, metals in general are much more resistant to the conditions of space radiation (compared to polymers). However, difficulties exist concerning shape control. Also, foil membranes need to be very thin for folding purposes and this limits the application to this technology to those structures that are not exposed to high stress.

Foam Inflation

In this proposal, the skin of the inflatable structure does not stiffen by itself. Instead, liquid polymeric foam is injected into the cavities of the inflatable structure and causes the structure to erect. When the foam expands upon cure, the structure is pressurized and obtains its shape. Upon hardening of this foam, a rigid structure is obtained having the same shape as the enclosing envelope. In essence, the enclosing envelope serves

as form and external skin for the structural foam core. A sandwich structure is obtained exhibiting excellent strength-to-weight ratio and impact resistance. A few drawbacks exist. First, because expanding polymeric foam is used for inflation, designs options tend to be more limited since pressure is not distributed as effectively or uniformly. The level of structural refinement is therefore less than for gas inflated structures. Further, most polymer foams exhibit significant shrinkage upon cure, making it hard to accomplish accurate shape control. The technology is further limited by the selection of those foams that can harden under space conditions. The use of in-situ foam in combination with rigidified skins is also proposed as a method to increase strength and impact resistance for RPC [Cadogan, 1998].

Passive Cooling

In this proposal, the characteristic of thermoplastic polymers to soften upon heating above the glass transition temperature (Tg) is exploited (figure 2.11). A membrane structure is constructed of a polymer that is rigid under normal service conditions. In order to deploy the structure, the membrane material is heated above its Tg. Since above Tg, the material behaves like a rubber, the structure can be inflated [Cadogan, 1998]. This is basically the same process as the stretch- blow-molding process used to make soda bottles, or the thermoforming process used to make Plexiglas® skylights (only, no molds are used).

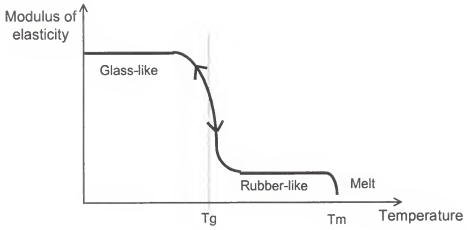


Figure 2.11 Temperature response of thermoplastic polymers

CHAPTER 3
RPC: SOME THEORETICAL SOLUTIONS

Rigidized Pneumatic Composites (RPC) are defined as thin flexible membrane structures that are pneumatically deployed. After deployment, these structures harden due to chemical or physical change of the membrane. Because of this change, these structures do no longer require pneumatic pressure to maintain shape or provide structure. The exploration and development of materials that are tailored towards application of this technology in the construction field is the main focus of the research presented in this dissertation. The idea to rigidify pneumatic structures is fairly new and not yet well established. As already mentioned, most of current research is concentrated in the design of space structures. The displacement of these technologies into architectural applications is not a straightforward process. Conditions in space differ significantly from those encountered on Earth, and solutions presented need to be tailored towards the specific environment. A general discussion describing workable concepts for solidifying membrane structures is presented. The focus of this search was to identify processes that can be used to stiffen polymeric membranes. Systems that are foam-inflated, or rely on strain-hardening are not included.

Material Performance Criteria

Many systems exist or can be invented that can be used to stiffen a polymeric membrane structure. However, taking under consideration the conditions necessary to come to an acceptable system, a solution does not present itself easily. This is due to the fact that a combination of performances is required. While solving for one criterion is

relatively easy, solving for all is much more complicated. The application of this technology in construction requires the development of unique materials tailored towards the specific applications. A number of materials and system criteria apply. First, an elastic type of material is needed that allows for convenient fabrication, storage, and pneumatic erection of the RPC structure. Secondly, the membrane needs to be able to stiffen sufficiently according to the demands of structural design (see chapter 5). Further, materials and manufacturing processes must be economically and environmentally feasible and attractive. Finally, the process of rigidification needs to occur in a well-controlled manner, posing not to many restrictions on environmental conditions that can be encountered on a construction site.

Theoretical Solutions

RPC structures are pneumatically shaped. After rigidification, membranes are designed to withstand both tensile and/or compressive stresses. To accomplish this objective, the physical properties of the membrane need to be altered from an elastic rubber-like behavior (low modulus) into a stiffer more glass-like material (higher modulus). For polymeric materials, this objective can be accomplished in several ways. Polymeric materials are macro-molecules that can be designed to exhibit a variety of properties. The physical properties of polymers are controlled by many factors including: polymer structure, morphology, cross-link density, inter-molecular attraction, chain mobility and stiffness, temperature, molecular weight, and free volume [Rosen, 1993]. Table 3.1 summarizes the effect that the various factors have on polymer properties. In essence, for a polymer to be elastic at a specific temperature, polymer chains need to be mobile enough to strain when a force is applied upon them. Polymer chains that are highly cross-linked, are crystalline, or have a rigid backbone are very restricted in motion and are therefore not elastic but exhibit glass-like behavior. On the other hand,

polymeric chains that are amorphous and have a sufficiently flexible backbone (at specific temperature) have the ability to deform in an elastic manner. To prevent plastic deformation however, polymer chains should be prevented from slipping past one another when strained. Chain slippage can be prevented by slightly cross-linking the polymeric chains to one another. Such cross-linking can be accomplished by means of permanent covalent bonds or by incorporating small crystalline regions that connect and prevent slippage of polymer chains (figure 3.1).

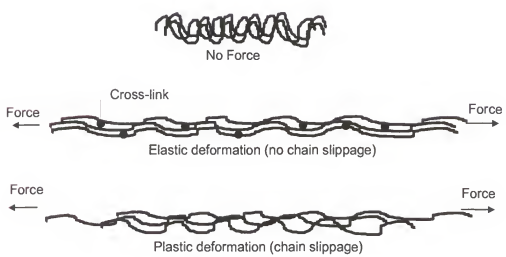


Figure 3.1 Cross-linked and non cross-linked polymers

Table 3.1 Relationships between modulus of elasticity and polymer feature

Controlling Factor	Action	Effect on Modulus
Molecular weight	Increase	Increase
	Decrease	Decrease
Crosslink density	Increase	Increase
	Decrease	Decrease
Chain rotational stiffness	Increase	Increase
	Decrease	Decrease
% Crystalline	Increase	Increase
	Decrease	Decrease
Inter molecular attraction	Increase	Increase
	Decrease	Decrease
Temperature	Increase	Decrease
	Decrease	Increase
Free volume	Increase	Decrease
	Decrease	Increase

Table 3.1 summarized the actions that can be taken to increase the modulus of elasticity of polymeric materials. Hence this table also summarizes the list of possible actions to stiffen a polymeric membrane for application in RPC technology. The factors listed in table 3.1 do not act independently from one another. Increasing cross-link density for example will both increase molecular weight and chain rotational stiffness. Also, increasing crystalline content will decrease the free volume and increase chain rotational stiffness. So increasing molecular weight and crystalline content both result in a material with higher modulus of elasticity, although slightly different mechanisms may be at work.

Glass Transition Temperature

As stated above, polymeric chains that are amorphous and have a sufficiently flexible backbone have the ability to deform in an elastic manner (at specific temperature). Polymer chains that are highly cross-linked, are crystalline, or have a rigid backbone are very restricted in motion and are therefore not elastic but exhibit glass-like

behavior. So if elastic behavior is preferred for the un-stiffened RPC membrane, an amorphous polymer is preferred. It is well known that amorphous polymers can exhibit two distinct types of mechanical behavior depending on the temperature at which they are tested. Amorphous polymers behave in a rubber-like manner when tested above the so called glass-transition temperature (Tg), while they behave in a glass-like manner when tested below Tg (figure 3.2). If an amorphous polymer is rubber-like or glass-like at use temperature will thus depend on the glass transition temperature.

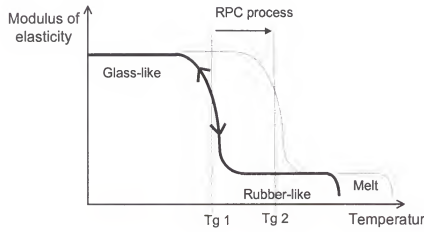


Figure 3.2 Temperature response for amorphous thermoplastic polymers

Controlling the mechanical properties of amorphous polymer can thus be restated as controlling the polymer's glass transition temperature. RPC technology can therefore be described as a shift in the polymers Tg from below the temperature at which the structure is inflated to above the temperature at which the final structure will operate. The means available to do so are the same as those listed in table 3.1 It is clear that

since so many controlling factors exist, a list of possible systems (single or combined actions) will always remain incomplete. Nevertheless, a framework can be established to aid in future development of specific material solutions.

Increasing Molecular weight

Structural polymeric materials are obtained by polymerization of small molecules into large polymeric chains or networks. Both step and chain growth reactions can be used. The longer the polymeric chains are, the more interactions exist in-between adjacent chains, and the more energy is needed to separate them. Mechanical properties and glass transition temperature of polymers varies according to the empirical relation: $Tg = T_g^{\infty} - C/x$ Where C is a constant for the particular polymer, Tg is the asymptotic value of T_g^{∞} at infinite chain length, and x is the polymer chain length. For most commercial polymers x is high enough so that $Tg \approx T_g^{\infty}$ [Rosen, 1993]. Since good initial strength is required from the RPC membrane, chain length will need to be sufficiently high initially. Extending the chain length of the polymer therefore provides little opportunity for increasing Tg or modulus of elasticity. Only if a very low molecular weight polymer is used will this method of stiffening have opportunity in RPC application. A low molecular weight polymer, depending on the chain length and type of polymer used, can behave as a paste-like semi-solid material. Since such materials have insufficient strength by themselves to be used as an RPC membrane they will need to be supported by some other mean. Impregnation of a fabric or support by a second membrane may proof useful for use in RPC type of system.

Increasing Cross-link Density

Infinite molecular weight implies polymerization into a highly cross-linked network. Rotation and chain slippage of highly crosslinked networks can only occur when strong

covalent bonds are broken, hence these materials have high modulus and generally fail in a brittle manner [Rosen, 1993]. By controlling cross-link density, properties of network polymers can be tailored. Cross-linked polymer networks can be formed in two ways: (1) by polymerization of monomer mixtures that contain sufficient amount of tri- or higher functional monomers, or (2) by chemically creating cross-links between previously formed linear or branched polymeric molecules. Both methods can be applied in RPC technology.

Cross-linking of multi-functional monomers

When applying the first method, a pre-preg material can be used. The fabrication of pre-preg involves a two-step approach. First, a monomer mixture containing sufficient tri- or multi-functional monomer is cured to a certain degree of conversion after which polymerization is stopped (figure 3.3). Such materials are called B-staged resins. The degree of cure (conversion) determines the viscosity of the resin. B-staged resins can have viscosity's ranging from semi-liquid to semi-solid. After the desired consistency is reached the cure reaction is stopped and the system is stored under conditions that prevent further cure. When fiber reinforcement is impregnated with a resin and cured to B-stage, a pre-preg is formed. Depending on the degree of conversion, such pre-pregs can be used as a membrane to build a pneumatic composite. After inflation, the membrane can be further cured into a more tight network polymer resulting in higher E and Tg. Typical example are pre-preg's made from B-staged epoxy resin systems. For application in RPC technology, this is currently the most prevailing method. These systems have the advantage that a wide variety of pre-preg materials are commercially available. The disadvantages are that these materials are often expensive because of the time involved to bring a resin to B-stage, and B-staged resins further need to be stored at low temperatures to prevent further cure. Also, shelf live is usually limited to

about one year. These conditions put severe limitation on the usefulness of this technology in the construction industry (cost & storage conditions).

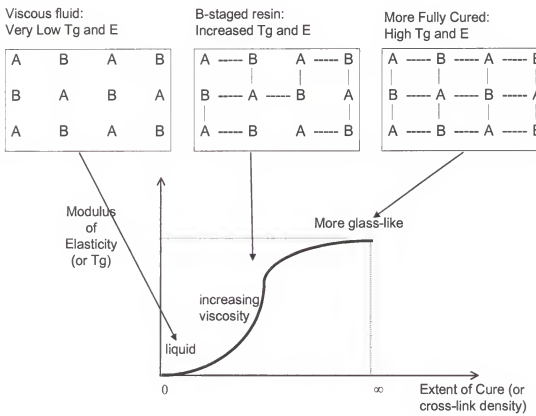


Figure 3.3 B-Staged resin, Increased E and Tg with increasing Cross-link density

Cross-link linear or branched polymers

The second method of obtaining highly cross-linked network polymers involves the chemical cross-linking of a pre-formed linear or branched polymer. Figure 3.4 serves as illustration of this approach. For application in RPC technology, several options are open for investigation. A linear polymer (A) containing some functionality in its main chain or

pendant group can be diluted with a monomer / plasticizer (b). After cure, monomer molecules combine with functional side groups of the main polymer to form a highly cross-linked network. If functional groups incorporated into the polymer main chain (A+x) have the ability to combine with one another, a tightly cross-linked network can be obtained as well. Example of the first system is the cross-linking of unsaturated polyester with styrene, and the cross-linking (vulcanization) of unsaturated 1,4-polybutadiene with sulphur. Examples of the second system is the cross-linking of polymers containing SH-side-groups or unsaturated bonds such as found in 1,2-polubutadiene.

Increase Crystalline Content

Increasing crystalline content is an effective way of improving overall performance of a polymer. Depending on type and orientation of the crystal lattice, polymers with extraordinary strength, stiffness, and glass transition temperature can be obtained. The effect of increased crystalline content is a decrease in polymer free volume and an increase in the intermolecular attraction. Both these events will increase Tg and modulus of elasticity of the polymer. Figure 3.5 illustrates the relationship between E and crystalline content. The type of crystal lattice that can be formed depends on the regularity and flexibility of the polymer backbone as well as processing conditions. In general, polymers with a regular and flexible backbone, such as polyethylene, form crystals easily. Irregular polymers or polymers with bulky and irregular side-groups do not pack easily into a crystal lattice. A similar process in which the chains (or side-groups) of an amorphous polymer can be transformed into a crystal lattice by means of a thermal annealing process may prove useful in RPC technology. The potential of a reversible process may further have a significant advantage in terms of recycling potential.

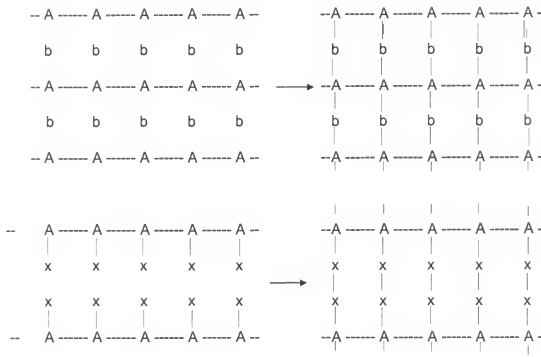


Figure 3.4 Cross-linking of linear or branched polymers

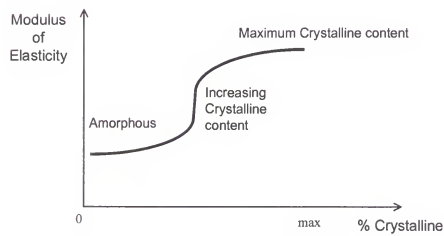


Figure 3.5 Increase in modulus of elasticity with increasing crystalline content

Increase Inter-Molecular Attraction

The stronger the attractive forces between molecules, the stronger they are bonded together, and the more energy will be required to produce motion [Rosen, 1993]. Controlling non-covalent bonding in polymers is thus an effective way to alter polymer mechanical and thermal performance. The primary non-covalent bonds in polymer systems are hydrogen bonding, dipole interactions, ionic bonding, and van der Waals forces. The mutual attraction of polymer chains due to the various bonds is a function of the distance between polymer chains and type of secondary bond. For application in RPC technology, controlling non covalent bonding may also prove useful. A number of ways may be available to do so.

Increasing secondary bonding

If the amount of secondary bonding can be increased, mechanical and thermal properties of a given polymer will increase. Ionomers are a class of polymers designed to exploit this ability. Positive charged metal ions that are distributed in-between polymer chains form strong secondary ionic bonds with negative charged atoms present at the polymers backbone. In the absence of positive metal ions, polymer chains are not attracted to one another, introducing positive ions increases attraction enhancing polymer mechanical and thermal properties [Odian, 1991].

Evaporation of plasticizer

Attractive forces in polymers can be disrupted by means of an external plasticizer. The function of a plasticizer is to force apart polymer chains so that more free volume comes available to move around. A plasticizer usually is a small molecule that forms strong secondary bonds with the polymer backbone. Because of this action, polymer chains are shielded from one another. Depending on the level of plasticizer added, this action may result in decreased mechanical and thermal performance. If the plasticizer is

removed from the polymer at a later stage the process is reversed and mechanical and thermal properties of the polymer will start to increase. Figure 3.5 relates mechanical performance of a polymer to the amount of plasticizer added.

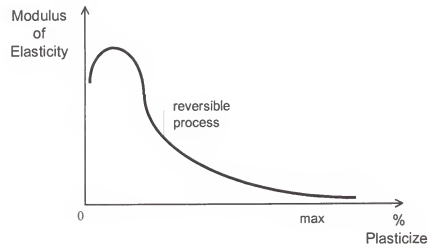


Figure 3.5 Change in modulus of elasticity with changing plasticizer content

Application of plasticizer evaporation in RPC technology may also prove to be a useful concept. This approach is identical to evaporating water from a wash-leather. When the leather is soaked in water it remains plastic, after the water has evaporated the leather becomes hard and stiff. The principle in this case is simple, small water molecules disrupt polymer-polymer interaction (leather is a polymer) by forming secondary bonds with the polymer molecules and spreading them apart. In this way polymer molecules have more free volume to move around, providing a more plastic mass (figure 3.6). Many other polymers behave in a similar manner and many different types of solvents other than water can be used. This approach is attractive in RPC technology since no chemical reactions are involved. Also, the process is reversible providing increased

opportunity for recycling. Further, many candidate polymers and plasticizers are available to develop a range of different systems. Examples are cellulose-based polymers, poly-vinyl-chloride, poly-sulfones, and acrylate based polymers. Some of the disadvantages are polymer shrinkage upon plasticizer evaporation. Also, possible pre-mature leach out of plasticizer during storage might cause some problem. Care must further be given to select those plasticizers that are not harmful to the environment

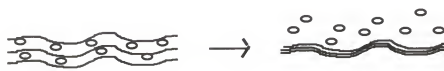


Figure 3.6 Evaporation of plasticizer

Decreasing Polymer Free Volume

The free volume of a polymer is the volume of the polymer mass not actually occupied by the molecules themselves [Rosen, 1993]. The higher the free volume, the more room the molecules will have to move around. The more free volume available, the lower Tg and mechanical properties will be. The action of a plasticizer described above clearly describes this concept. Hence, increasing free volume and decreasing inter molecular attraction go hand in hand. For application in RPC technology, the evaporation of plasticizer provided a good example. Another approach is to polymerize the plasticizer instead of evaporation.

Polymerization of a plasticizer, sequential semi-IPN

This approach is very similar to the solution presented above; again small molecules disrupt polymer-polymer interaction leaving a more plastic mass. The difference from the previous solution is that the plasticizer is not evaporated but transformed into a polymer network itself (figure 3.7). After polymerization, a solid polymer replaces the free volume previously provided by the plasticizer. Because of this, the freedom to move is reduced and the original polymer will become stiffer. In addition, the second-phase polymer adds its own specific strength to the system. Such materials are called Interpenetrating Polymer Networks (IPN). IPN's are defined as a combination of two or more polymers in network form that are synthesized in juxtaposition. Semi-IPN's consist of an intimate mixing of a linear or branched polymer with a cross-linked polymer [Sperling, 1986]. IPN's have the advantage of creating new organic materials by combining the properties of known polymers. Again a number of polymers can be used and many reactive plasticizers can be considered. A reactive plasticizer is really a monomer that possesses good compatibility with a given polymer regarding ts plasticizing properties. Relative to the previous solution, this approach becomes a little more complicated since it involves a chemical reaction. The formation of semi-IPN's possess some of the same merits as the system in which plasticizers are evaporated. First, plasticizer technology is well established and a range of polymers and reactive plasticizers are available. Further, by proper selection of initial polymer and reactive plasticizer, final polymer properties can be well controlled. Relative to plasticizer evaporation, less shrinkage is also to be expected. Disadvantages of this system include possible leach out of plasticizer during storage, and leach out after cure due to incomplete conversion of reactive plasticizer into polymer.

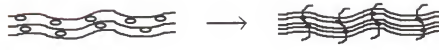


Figure 3.7 Polymerization of a Plasticizer, sequential semi-IPN

Internal plastification, functional side-groups

The purpose of a plasticizer is to increase the free volume between polymer chains disrupting secondary polymer-polymer interactions. The same effect can be accomplished with polymer chains that have bulky side-groups that behave as a plasticizer. When these side-groups are functional, that is having the potential of forming bonds with other side groups, the original polymer can be transformed into a rigid cross-linked network (figure 3.8). This approach is the same as the cross-linking of preformed polymer as described above. Compared to plasticizer evaporation or IPN-formation, this system has the advantage that no plasticizer leach-out during storage can occur.

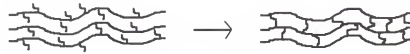


Figure 3.8 Internal plastification, functional side-groups

Increasing chain rotational stiffness and immobility

If polymeric chains are prevented from rotating about covalent bonds, Tg and modulus of elasticity will increase. Such polymers can be accomplished by incorporating bulky side-groups or by designing polymers with a stiff ladder-type of structure. For application in RPC technology, rotational stiffness can be increased in a number of ways. In essence, increasing cross-link density, crystalline content, inter-molecular attraction, and decreasing polymer free volume all accomplish this objective. The same techniques described above can thus be applied to accomplish this objective.

Decreasing temperature

The properties of amorphous polymers strongly depend on temperature, being-glass like below Tg and rubber-like above Tg. As discussed in chapter 2, passive cooling exploits this ability in RPC technology. Although very simple in concept, some restrictions apply that make application of this approach less attractive for regular construction. First, to prefabricate, pack, and unfold the RPC structure the preferred material behavior at room temperature is that of a rubber. Since the final structure needs to be rigid at normal use temperature, the entire membrane needs to be heated above this temperature to allow for pneumatic erection. This is a very cumbersome process that may not always be safe to conduct. Further, the membranes need to stay above Tg sufficiently long to allow for complete pneumatic deployment, this places further practical limitation on structure size and complexity. This approach may prove to be more useful for space-applications. In such an environment, heat can easily be obtained from the sun and subsequent cooling below Tg can be accomplished by shielding the structure from solar radiation.

Controlling the Stiffening Process

The successful implementation of RPC technology poses many demands on material performance. First the material needs to be able to stiffen sufficiently after pneumatic erection. The means to accomplish this objective have just been discussed in the previous section. Of equal importance is to develop a process in which this stiffening process can be easily controlled, especially considering the broad range of environmental conditions that are commonly encountered on a construction-site. A number of approaches will be presented in this section that may allow for such control.

Systems Requiring Chemical Cure

Some of the mechanisms to stiffen polymeric membranes require chemical reactions. These include polymerization of a reactive plasticizer, cross-linking of B-staged resins, and cross-linking of polymers containing reactive side-groups. A tremendous amount of chemical reactions exist or can be thought of that can accomplish such results. In essence, the induction of any chemical reaction is controlled by the amount of energy needed to accomplish sufficient cure. In some way or form, this energy needs to be delivered to the complete membrane surface and throughout the thickness of the RPC structure. Energy can be delivered directly in the form of thermal, electromagnetic, or mechanical energy. Energy can also be delivered indirectly through release of energy contained within gaseous or liquid molecules applied to the membrane. Finally, energy needs can be decreased by use of catalysts that reduce the activation energies needed for the specific reaction. In this case, an efficient catalyst delivery or release system is needed. A brief description of restrictions and consideration for some energy delivery systems is provided here.

Thermal cure

Depending on the mechanism of stiffening the RPC membrane, increase of temperature can serve as a means to trigger a number of chemical reactions. In free radical polymerization, elevated temperatures can be used to decompose peroxide initiators, that in turn initiate free radical chain reactions. A free radical reaction can in turn serve to cross-link an existing polymer or to initiate the polymerization of a reactive plasticizer to form an IPN. Elevation of temperature can also be used to accomplish cure of step-polymerization reactions. Elevated temperature can be accomplished in a number of ways. For example, by means of electrical resistance wires embedded in the membrane, by means of solar radiation, or by means of hot gas circulated through the membrane structure. Certain general restrictions apply to systems that are thermally cured. First, the cure temperature should be higher than the temperature encountered during storage or transportation. Since storage at normal temperatures is preferred over cold storage, depending on location of application, cure temperature should be higher than temperatures that can be encountered on a hot summer's day. If cold storage is an option, a lower cure temperature can be selected.

Light cure

Polymerization and cross-linking can also be induced by means of visible or ultra-violet light. By selecting a proper photo-initiator, systems can be developed that are thermally stable at normal storage and transportation temperatures. Both natural and artificial light sources can be used. UV-cure is preferred over visible light since the latter can cause premature cure of the membrane when exposed to light during manufacture, transportation, or pneumatic erection. When light-cure is used, restrictions apply to penetration depth. If thicker membranes or more complex structural designs are used, full exposure may cause some practical problems.

Gas cure

Systems that are gas-cured have the advantage that even for very complex structural designs each part of the membrane will be treated uniformly. Sufficient time needs to be available to allow the gas to permeate throughout the thickness of the membrane, membranes that are more permeable may speed up this process. When gas-cure is used, some safety hazards may occur since gasses that are chemically reactive are often also harmful to health or environment. Developing gas-cured systems that are safe to use is therefore preferred. For practical and economical reasons, the gas selected should also be readily available and have low cost. Less strict economic and environmental restrictions apply for space applications.

Cure with liquid or aerosol

Cure with liquid reactants may also be an option. If reactants are relatively harmless, direct application by means of spraying onto the membrane may be possible. Dispersion as an aerosol within the inflating gas is also feasible. The same concern as gas cured systems applies in that penetration throughout the membranes thickness may be needed to accomplish full cure. Membranes that are more permeable may therefore be needed.

Systems Requiring no Chemical Cure

Some of the mechanisms to stiffen a polymeric membrane described in a previous section required no chemical reactions. These included evaporation of plasticizer, strain hardening, increase of crystalline content, or passive cooling techniques. Although no chemical reactions are involved, these systems also require some energy input. Strain hardening for example requires mechanical energy, which can be efficiently provided by means of the pneumatic pressure. Evaporation of plasticizer proceeds only when sufficient vapor pressure is available. This pressure will depend on the surrounding

conditions of temperature and humidity. Passive cooling further requires increase of temperature above Tg. Increasing the crystalline content may require both thermal and mechanical energy. For thermal energy needs, the same restrictions and considerations apply as for chemically cured systems. Mechanical strain energy may perhaps be the most convenient to deliver. However, this approach may prove difficult when high strength fibers are used to reinforce the membrane.

CHAPTER 4
EXPERIMENTAL WORK

Current efforts to develop RPC technology are focused on space structure design [Cadogan, 1998]. The materials used or proposed for such applications are mainly high performance pre-preg laminates. For space structure design, material cost is usually not a design-controlling factor. For lower-tech applications of RPC technology, such as affordable housing, material cost becomes critically important and lower cost substitutes need to be identified. The typical cost of a simple E-glass continuous-fiber epoxy pre-preg is about 22 $/Kg [Callister, 2000]. However, the total material cost to build for example a simple house is still relatively high considering that about 400 Kg of material are needed to construct a 1200 SF house (see chapter 6). In an effort to reduce this material cost, a new material was proposed and tested as part of this dissertation. This material is based on the forming of a sequential semi interpenetrating polymer network (semi-IPN). Interpenetrating polymer networks (IPN's) are defined as a combination of two polymers in network form, at least one of which is synthesized and/or cross-linked in the immediate presence of the other. Semi-IPN consists of an intimate mixing of a linear polymer with a cross-linked polymer. Sequential IPN are IPN's in which polymer network 1 is first synthesized. Then, monomer 2 plus cross-linker and activator are swollen into network 1 and polymerized in-situ [Sperling, 1996]. Since the first known published report on such material appeared in 1914 by Aylsworth, IPN's appear to be invented and reinvented over and over again. An historical overview of IPN development is provided by Sperling [Sperling, 1986]. IPN's have continued to attract the attention of polymer

chemists since they permit one to create new organic materials having tailored-made properties by combining the properties of existing polymers. A review of current status of research on IPN's is provided by Sperling [Sperling, 1996]. A number of papers have appeared in the literature that describe sequential semi-IPN's based on PVC and reactive plasticizers. Zahran for example reports on the effects of gamma radiation on the mechanical properties of PVC plasticized with diallyl phthalate, rendering a rigid material with increased tensile strength [Zahran, 1985]. Ismat describes a process in which liquid reactive monomers function as plasticizers for PVC. After curing of the monomer, the new polymer acts as an impact modifier and decreases the brittleness of the original polymer. Various acrylic monomers were tested in combination with PVC, thermal initiators were used to induce polymerization [Ismat, 1991]. Moussa and Decker report on the photo-cross-linking of acrylic monomers in polymer matrixes. Polymers tested included poly-methyl-methacrylate (PMMA), poly-vinyl-chloride (PVC), and polystyrene (PS). In this approach, acrylate based monomers serve as plasticizer for the various polymers. Photo-initiator and monomer were added to a polymer solution after which the solution was cast on a plate and dried to obtain a solid rubber-like film. It was observed for example that PVC-film containing tri-methyl-propane-tri-acrylate monomer (TMPTA), when exposed to UV radiation, the rubber-like low modulus film would change into a high modulus glassy polymer in a very short time. The glass transition temperature (Tg) of the TMPTA-PVC network was found to be located at around 130 °C, i.e. 50 °C above the Tg of virgin PVC. Unfortunally, no mechanical properties were listed for these materials. [Moussa and Decker, 1993]. A similar study was published later repeating earlier findings [Kaczmarek and Decker, 1994]. The formation of sequential semi-IPN's based on poly-vinyl-chloride (PVC) and a reactive plasticizer is of particular interests in the development of RPC technology for a number of reasons

including: 1) PVC is a low cost polymer. 2) Plastification of PVC by means of external plasticizers rendering a rubber-like material is a well-established technology. 3) A vast array of monomers exist that can serve as plasticizers for PVC, including both synthetic and natural products. 4) Plastisol technology, a technique to produce plasticized PVC membranes or coated fabric provides a common and inexpensive technique for making membranes. The use of photo-initiator to induce polymerization as described by Moussa and Decker further provides a convenient way to cure the membrane of a pneumatic structure [Moussa and Decker, 1993].

Scope and Objectives

The formation of sequential semi-IPN's based on poly-vinyl-chloride (PVC) and a reactive plasticizer using photo-initiator is of particular interests in the development of RPC technology for the reasons stated above. Unfortunate, no mechanical performance data could be found in the literature for such materials. In addition, the methods used to make plasticized PVC film involved solution casting techniques. It is well known that plastisol coating is a much more efficient method for making thin membranes. In plastisol coating, mixtures of fine PVC powder (particle size ≈1micron) and plasticizer are prepared. After careful mixing of PVC and plasticizer, a paint like viscous slurry is obtained for which the viscosity is function of the amount and type of plasticizer added. When making a thin film from this slurry, the viscous mixture is cast onto a steel drum and brought to uniform thickness by means of a doctor blade. After this, the plastisol mixture is heated uniformly to a temperature that is high enough to allow the PVC molecules to relax and adsorb the plasticizer. After cooling down to ambient temperature, a uniform film of dry plasticized PVC film is obtained. Figure 4.1 illustrates this process. This method can also be used to coat various fabrics with a layer of plasticized PVC.

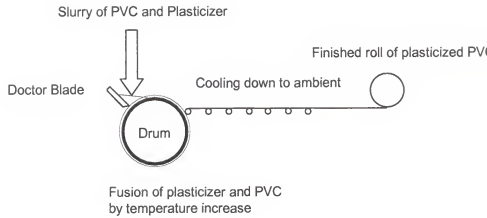


Figure 4.1 Plastisol process for making plasticized PVC film

With regard to this process however, it is uncertain if the mixture of reactive plasticizer and photo-initiator can survive the elevated temperatures encountered during this manufacturing process (≈200°C for 10 minutes) without the occurrence of premature polymerization of the reactive plasticizer. The main objectives of the experimental work included in this dissertation are therefore to:

1) Collect data for mechanical properties for this material, i.e. tensile strength and modulus of elasticity.

2) Propose a system (PVC + monomer + photo-initiator) that can survive processing conditions encountered during the plastisol manufacturing process (≈200°C for 10 minutes).

In addition to these questions, it was also of interest to evaluate the mechanical performance of this semi-IPN matrix system in combination with various thin fiber-reinforcement fabrics. For this reason, the experimental work also included testing of three different types of fabric that were coated with the semi-IPN material. The fabric materials that were tested included glass, Kevlar, and cotton fiber. Composite samples

were prepared and tested in 3 different angles relative to the fabric's warp direction (0°,22.5°, and 45°).

The experimental work included in this dissertation should be regarded as a pilot study aimed to assess the feasibility of the proposed system. It is clear that in addition to the above questions, various additional information is needed before a successful product can be marketed. These questions include for example long-term plasticizer/PVC compatibility, plasticizer toxicity, shelf life, long-term durability of this material, and ease of recycling. These issues were not addressed because of restraints on time and resources. The focus of the experimental work was to assess the feasibility of the use of sequential semi-IPN's as a general system for use in RPC technology.

Materials

IPN-Matrix

All components for the making of the PVC based sequential semi-IPN were commercially available products, all were used as received. The photo-polymerizable material was made up of four basic constituents:

1) A solid PVC resin, a dispersion grade PVC powder commonly used in plastisol applications (Geon Resin 129 from the Geon Company).

2) A reactive plasticizer was obtained from Sartomer (SB520A20) and consisted of a blend of acrylate oligomer diluted with an acrylic monomer (tri-propylene-glycol di-acrylate). This blend showed good compatibility with the PVC resin and was recommended by Sartomer for elevated process temperatures (≈200°C for 10 minutes) and use with PVC.

3) A photo-initiator that cleaves readily upon UV-exposure to generate free radicals (Irgacure 369 from Ciba Chemicals). This initiator was recommended by Ciba Chemicals for use in the plastisol application. The initiator was believed to withstand elevated

temperatures for short periods of time without premature decomposition (≈200°C for 10 minutes).

4) A stabilizer system for the PVC resin. Epoxidized linseed oil (Flexol LOE from Union Carbide) in combination with CaZn (Thermcheck SP239 from Ferro) was used for this purpose.

Fiber- Reinforcement

Glass fiber

Glass fiber reinforcement fabrics was obtained from BGF Industries Inc. The glass fiber fabric consisted of E-Glass (Electrical) with continuous filament having an average filament diameter of 6 microns. Fabrics were not finished and were used as received. Table 4.1 summarizes glass fabric characteristics and properties.

Table 4.1 Characteristics Glass Fiber Fabric

STYLE:	1677	
FINISH:	Greige	= not finished
WEAVE:	Plain	
WARP:	ECDE 150 1/0	= E-glass Continuous, 6 micron
FILL:	ECDE 150 1/0	= E-glass Continuous, 6 micron
COUNT:	78.74 X 78.74	Ends x Picks per 5 cm
WEIGHT:	107.82	Grams/m2
THICKNESS:	0.1066	mm
BREAKING STRENGTH:	1795 x 1225	N/5cm (warp x fill)

Aramid fiber

Aramid fiber reinforcement fabrics were obtained from BGF Industries Inc. The aramid fiber fabric consisted of Kevlar fibers, the fabric was finished applying a scouring

process for removal of extractable material (to less than 0.1%), the fabric was used as received. Table 4.2 summarizes aramid fabric characteristics and properties.

Table 4.2 Characteristics Aramid Fiber Fabric

STYLE:	5120	
FINISH:	618	
WEAVE:	Plain	
WARP:	195 T965 Kevlar®49	
FILL:	195 T965 Kevlar®49	
COUNT:	66.929 X 66.929	Ends x Picks per 5 cm
WEIGHT:	57.63	Grams/m2
THICKNESS:	0.1016	mm
BREAKING STRENGTH:	1751 x 1751	N/5cm (warp x fill)

Cotton

A symmetrical plain weave fabric of unbleached cotton was obtained containing approximately 142 ends and picks per 5 cm fabric. The thickness of the fabric was approximately 0.15mm. No further data was available for this material.

Methods

Plastisol mixes were prepared that contained 100 parts by weight (pbw) of PVC, 70 pbw of reactive plasticizer, 15 pbw of epoxidized linseed oil, 1 pbw of CaZn, and 0.3 pbw of photo-initiator. Table 4.3 summarizes plastisol composition. The amount of plasticizer that is commonly used in plasticized PVC film ranges from 60 to 80 pbw depending on the type of plasticizer and the final application. The plastisol mixture prepared thus contained a fairly high amount of plasticizer. The composition of the sequential semi-IPN as described by Moussa and Decker contained 100 pbw of reactive plasticizer [Moussa and Decker, 1993]. All plastisol mixtures were prepared in small glass beakers and were mixed by hand using a spatula.

Table 4.3 Plastisol composition

IPN Component	Product name	Resource	Parts by weight
PVC	GEON 129	GEON	100
Reactive Plasticizer	SB520A210	Sartomer	70
Epoxidized Linseed Oil	Flexol LOE	Union Carbide	15
Photo-initiator	Irgacur 369	Ciba	0.3
CaZn PVC stabilizer	Thermcheck SP239	Ferro	1

Non-reinforced Samples

Tensile properties

Tensile properties were determined according to ASTM D638-96, standard test method for tensile properties of plastics. An aluminum mould containing five dog-bone (type IV) shaped negative forms was placed on a glass plate. Plastisol mixes were poured into these moulds. Moulds sitting on the glass plate were placed in an oven and heated for 10 minutes @ 190 °C in order to fuse the plastisol mix into a solid membrane. After cooling down to ambient temperature, the samples where removed from the moulds and exposed to UV-light for 10 minutes in sets of five. A 150 W xenon lamp placed at a distance of 60 cm was used for this purpose. Figure 4.3 shows a set of five samples after removal from the aluminum form. After cure, samples were sanded to uniform thickness. Forty seven samples where tested for tensile strength according to ASTM D638-96 using an Instron load frame. A crosshead speed of 2mm per minute was used for samples 1 through 25, a crosshead speed of 1 mm per minute was used for samples 26 through 47. All samples were tested at room temperature. Figure 4.4 shows all samples after the tensile test was completed.

Dynamic mechanical properties

Dynamic mechanical properties were measured according to ASTM D5418-95a, standard test method for measuring the dynamic mechanical properties of plastics using

a dual cantilever beam. Dynamic mechanical testing provides a method for determining thermo-mechanical properties of plastics. The properties of plastics can change dramatically depending on the temperature at which they are tested. At low temperatures, mechanical behavior may be elastic; that is, in conformity to Hook's law. At higher temperatures, viscous or liquid behavior prevails. For intermediate temperatures, the material can behave as a solid rubber that exhibits the combined mechanical characteristics of these two extremes. This condition is termed viscoelasticity. [Callister, 2000]. In Dynamic Mechanical Spectroscopy (DMS) measurements, a sinusoidal force is applied to a sample with known dimensions. The strain (or deflection) produced in the sample is then detected in function of time. When changing the temperature at which the sample is tested, the change in viscoelastic properties of the material can be identified relative to temperature. From this, major transitions within the material can be determined. Figure 4.2 illustrates the relationship between the viscous and elastic components for viscoelastic materials. When viscoelasticity is measured dynamically, there is a phase difference (delta) between the applied force and the resulting strain. In figure 4.2, E' represents the elastic or storage modulus of the material, E" represents the viscous or loss modulus, and delta represents the loss angle or phase difference between applied force and measured strain. Tan delta further represents the ratio of E"/E', E* represents the complex or combined modulus.

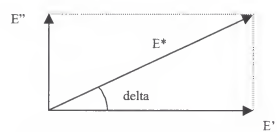


Figure 4.2 Elastic modulus relationships

When E" is smallest, the prevailing material responds is elastic. Hence, a peak for E" or tan delta indicates an increase in viscous behavior. These peaks also indicate major transitions for mechanical response relative to temperature.

Samples were prepared as follows; an aluminum mould with rectangular negative form was placed on a glass plate. Plastisol mixes were poured into this mould. The mold sitting on the glass plate was placed in an oven and heated for 10 minutes @ 190 °C in order to fuse the plastisol mixture into a solid membrane. After cooling down to ambient temperature, the sample was removed from the mould. The obtained flexible film was cut into the desired rectangular shape of approximately 50mm x 10mm, the sample thickness was approximately 1.5mm. After this, specimens were exposed to UV-light for 10 minutes, a 150 W xenon lamp placed at a distance of 60 cm was used for this purpose. The samples where clamped between the movable and stationary members of the dynamic mechanic spectroscopy apparatus (Seiko DMS110). A constant frequency of 1 Hertz was selected for all three tests. A linear temperature increase of 2 °C/min was used, testing started at a temperature of approximate -50 °C and was stopped at approximate 130 °C. Figure 4.5 shows the three samples that were tested.

Reinforced Samples

Tensile properties of reinforced samples were determined according to ASTM D5083-96, "standard test method for tensile properties of reinforced thermosetting plastics using straight-sided specimens". Plastisol mix was applied to the various fabrics and spread open evenly by means of a pallet. Impregnated fabric was placed in a tension ring stretching the fabric uniformly to flat configuration (diameter was approximately 25 cm). Flattened fabric was exposed for 10 minutes to three IR-light sources 250 W each at a distance of 15cm in order to fuse the plastisol mix into a solid

membrane. Samples were turned continuously to avoid local overheating. After cooling down to ambient temperature, the samples where exposed to UV-light for 10 minutes. A 150 W xenon lamp placed at a distance of 60 cm was used for this purpose. Specimens 25 mm wide and 170 mm long where cut out using a sharp knife, fiber angles where 0°, 22.5°, and 45° degree relative to the fabric's warp direction. Samples where tested for tensile strength using an Instron load frame according to ASTM D5083-96. A thin sheet of rubber was placed against both faces of the metal grip of the load frame to assure that the samples would not be damaged by the metal grip. Figures 4. 6 through 4.8 show some of the samples after tensile testing.

Figure 4.3 Set of five dog-bone samples after UV-cure, before testing

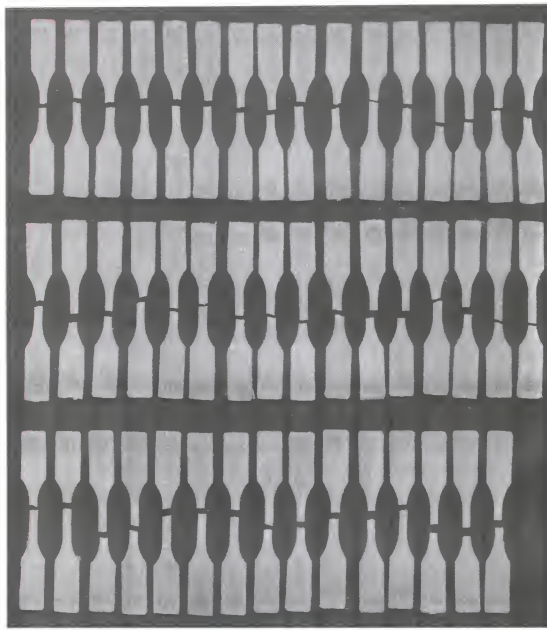


Figure 4.4 Dog-bone samples after tensile testing

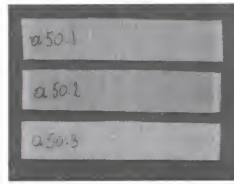


Figure 4.5 DMS Samples after testing

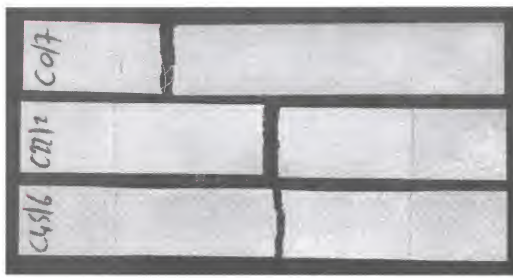


Figure 4.6 Cotton fabric reinforced samples, 0°, 22.5°, and 45° test angles

Figure 4.7 Glass fabric reinforced samples, 0°, 22.5°, and 45° test angles

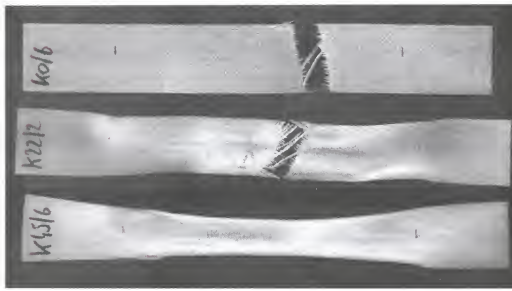


Figure 4.8 Kevlar fabric reinforced samples, 0°, 22.5°, and 45° test angles

Results

Non-reinforced Samples

Tensile test

For the above described matrix composition, the processing of the plastisol into solid plasticized film at 190 °C for 10 minutes did not result in premature polymerization of the reactive plasticizer. All samples remained flexible at room temperature (samples that were stored for more than one year still remained flexible, although some discoloration could be observed). After exposure to UV-light, all samples became rigid in just a few minutes. The average yield stress for the cured semi-IPN matrix was 25.5 MPa (N/mm^2). The minimum yield stress was 18.9 MPa, the maximum yield stress was 30.2 MPa. Figure 4.9 and table 4.4 provide the results obtained from the tensile tests for all 47 samples. Figure 4.10 provides a typical stress-strain curve for the semi-IPN.

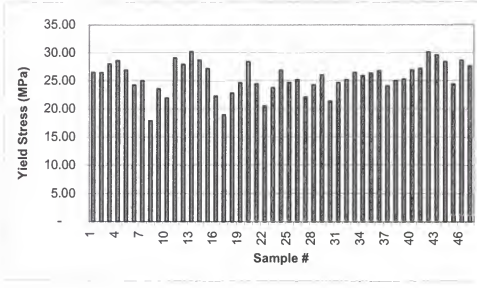


Figure 4.9 Yield stress semi-IPN matrix

Table 4.4 Yield stress semi-IPN matrix based on PVC and reactive plasticizer

Sample #	Thickness -average mm	Width-average mm	Area-average mm2	Yield force N	Yield stress N/mm2 (MPa)
A1	1.403	2.790	3.92	104	26.56
A2	1.603	2.960	4.75	126	26.55
A3	1.427	3.445	4.91	138	28.08
A4	1.447	2.895	4.19	120	28.65
A5	1.427	2.990	4.27	115	26.96
A6	1.617	3.005	4.86	118	24.29
A7	1.707	2.755	4.70	118	25.10
A8	1.703	3.050	5.20	93	17.90
A9	1.620	3.395	5.50	130	23.64
A10	1.717	2.810	4.82	106	21.97
A11	1.653	3.240	5.36	156	29.12
A12	1.583	3.295	5.22	146	27.98
A13	1.503	3.165	4.76	144	30.26
A14	1.607	3.160	5.08	146	28.76
A15	1.577	3.215	5.07	138	27.22
A16	1.310	3.010	3.94	88	22.32
A17	1.230	3.000	3.69	70	18.97
A18	1.557	3.060	4.76	109	22.88
A19	1.563	2.800	4.38	108	24.67
A20	1.523	2.845	4.33	123	28.38
A21	1.493	3.180	4.75	116	24.43
A22	1.660	3.205	5.32	109	20.49
A23	1.910	3.130	5.98	142	23.75
A24	1.790	3.160	5.66	152	26.87
A25	1.753	3.100	5.44	134	24.65
A26	1.707	3.420	5.84	147	25.19
A27	1.407	2.965	4.17	92	22.06
A28	1.590	2.750	4.37	106	24.24
A29	1.577	3.345	5.27	137	25.98
A30	1.430	3.015	4.31	92	21.34
A31	1.487	3.005	4.47	110	24.62
A32	1.457	2.975	4.33	109	25.15
A33	1.440	3.150	4.54	120	26.46
A34	1.503	3.135	4.71	122	25.89
A35	1.523	2.970	4.52	119	26.30
A36	1.590	3.105	4.94	132	26.74
A37	1.567	3.185	4.99	120	24.05
A38	1.553	3.140	4.88	122	25.01
A39	1.467	3.130	4.59	116	25.27
A40	1.630	3.150	5.13	138	26.88
A41	1.293	3.045	3.94	107	27.17
A42	1.480	3.415	5.05	152	30.07
A43	1.517	2.810	4.26	126	29.56
A44	1.370	2.870	3.93	112	28.48
A45	1.537	2.775	4.26	104	24.39
A46	1.440	2.885	4.15	119	28.64
A47	1.500	2.995	4.49	124	27.60
Average					**25.57**

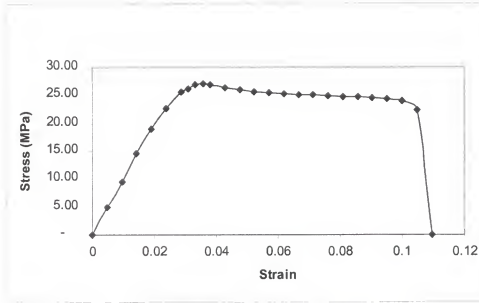


Figure 4.10 Typical stress-strain curve semi-IPN (crosshead speed 1 mm/min)

Dynamic mechanical properties

Figures 4.11 through 4.19 provide, elastic modulus (E'), loss modulus (E"), and tan Delta in function of temperature for samples a50.1, a50.2, and a50.3. Tables 4.5 through 4.7 provide similar information at distinct temperatures. Results for all three samples were found to be very similar. The peaks for tan Delta and the loss modulus coincides with a significant decrease in the elastic modulus (E'). These peaks occur approximately at 50 °C and 70 °C respectively, indicating a major transition region for this polymer. The elastic modulus is approximate 3.5 GPa at –45 °C, 3.4 GPa at -25°C, 3.11 GPa at 0°C, 2.65 GPa at +25°C, and 1.3 GPa at +50°C. The largest decrease in elastic modulus occurs between 50 °C and 70 °C indicating the region for the polymer's glass transition temperature.

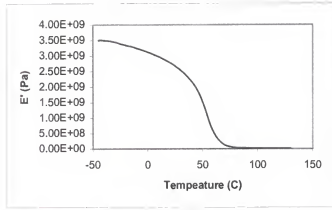


Figure 4.11 Elastic Modulus at different temperatures, sample a50.1

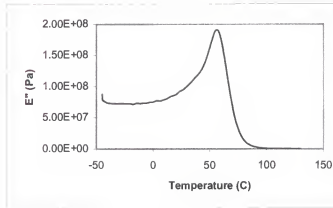


Figure 4.12 Loss Modulus at different temperatures, sample a50.1

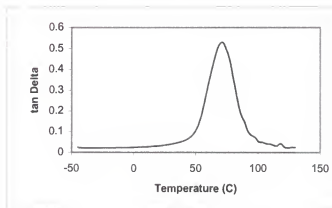


Figure 4.13 tan Delta at different temperatures, sample a50.1

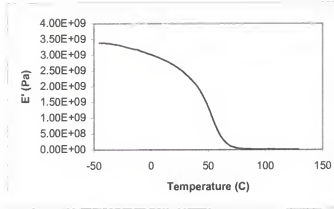


Figure 4.14 Elastic Modulus at different temperatures, sample a50.2

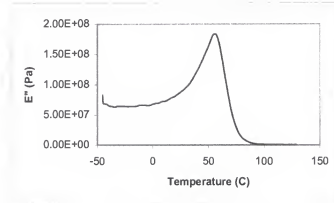


Figure 4.15 Loss Modulus at different temperatures, sample a50.2

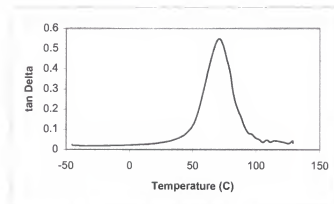


Figure 4.16 tan Delta at different temperatures, sample a50.2

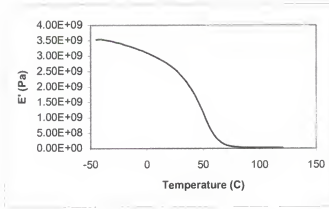


Figure 4.17 Elastic Modulus at different temperatures, sample a50.3

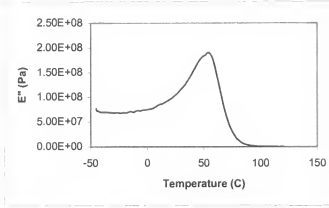


Figure 4.18 Loss Modulus at different temperatures, sample a50.3

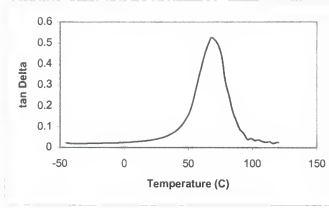


Figure 4.19 tan Delta at different temperatures, sample a50.3

Table 4.5 Selected E', E", E*, and tan Delta with changing temperature (sample a50.1)

Frequency	T	E'	E"	E*	tanD	Time
Hz	C	Pa	Pa	Pa		min
1	-44.9	3.50E+09	8.80E+07	3.50E+09	0.0252	0.13
1	-25.8	3.40E+09	7.24E+07	3.40E+09	0.0213	14.37
1	0.5	3.11E+09	7.54E+07	3.12E+09	0.0242	28.72
1	26.2	2.65E+09	9.46E+07	2.65E+09	0.0357	42.87
1	52.3	1.30E+09	1.76E+08	1.31E+09	0.1353	58.17
1	55.1	9.90E+08	1.90E+08	1.01E+09	0.1919	59.77
1	69.2	1.45E+08	7.56E+07	1.64E+08	0.5209	67.52
1	72	9.74E+07	5.15E+07	1.10E+08	0.5289	69.02

Table 4.6 Selected E', E", E*, and tan Delta with changing temperature (sample a50.2)

Freq.	Temp.	E'	E"	|E*|	tanD	Time
Hz	C	Pa	Pa	Pa		min
1	-45.2	3.38E+09	8.31E+07	3.38E+09	0.0246	0.13
1	-26.2	3.30E+09	6.47E+07	3.30E+09	0.0196	14.07
1	-0.2	3.03E+09	6.79E+07	3.03E+09	0.0224	28.25
1	25.2	2.56E+09	8.81E+07	2.56E+09	0.0344	42.33
1	51.6	1.22E+09	1.71E+08	1.24E+09	0.1394	58
1	54.3	9.65E+08	1.82E+08	9.82E+08	0.1884	59.53
1	68.3	1.49E+08	7.84E+07	1.68E+08	0.5273	67.23
1	71	9.74E+07	5.35E+07	1.11E+08	0.5493	68.75

Table 4.7 Selected E', E", E*, and tan Delta with changing temperature (sample a50.3)

Freq.	Temp.	E'	E"	|E*|	tanD	Time
Hz	C	Pa	Pa	Pa		min
1	-45.1	3.53E+09	7.75E+07	3.53E+09	0.0219	0.13
1	-26.1	3.43E+09	6.88E+07	3.43E+09	0.02	14
1	-0.7	3.11E+09	7.48E+07	3.11E+09	0.0241	27.83
1	24.4	2.59E+09	1.03E+08	2.59E+09	0.0399	41.88
1	51.3	1.06E+09	1.86E+08	1.07E+09	0.1759	57.45
1	54	8.27E+08	1.91E+08	8.49E+08	0.2305	58.97
1	70.4	1.14E+08	5.87E+07	1.28E+08	0.5164	68.1
1	73.1	8.25E+07	4.08E+07	9.21E+07	0.4945	69.6

Fiber-reinforced Samples

As expected, yield strength for the different semi-IPN composites highly depend on fabric orientation, being highest at 0° and lowest at 45°. The addition of cotton fabric apparently did not increase tensile strength of the matrix at the given volume fraction. However strength in all three measured direction where close to each other being 13.6 MPa, 12.1 MPa, and 11.3 MPa for the 0°, 22.5° and 45° directions respectively. Both the glass and Kevlar reinforced semi-IPN composites showed superior strength in the 0° direction, tensile strength were 191.5 MPa and 290.9 MPa respectively. Tensile yield strengths measured in the 22.5° and 45° directions were much lower for both the glass and Kevlar fiber reinforced composites. Table 4.8 summarizes the results for the various composite systems. Tables 4.9 through 4.11 provide the individual results for tensile yield strength for each of the samples / composite systems.

Table 4.8 Summary results fiber reinforced semi-IPN composites

Composite system	Test angle	Yield stress N/mm2	Fiber volume fraction (Vf)
Glass/semi-IPN	0	191.5	0.322
Glass/semi-IPN	22.5	12.5	0.427
Glass/semi-IPN	22.5	48.8	0.102
Glass/semi-IPN	45	11.8	0.36
Glass/semi-IPN	45	18.2	0.106
Kevlar/semi-IPN	0	290.9	0.375
Kevlar/semi-IPN	22.5	37.2	0.375
Kevlar/semi-IPN	45	21.6	0.258
Cotton/semi-IPN	0	13.6	0.246
Cotton/semi-IPN	22.5	12.1	0.183
Cotton/semi-IPN	45	11.3	0.196

Table 4.9 Yield stress for Cotton-reinforced semi-IPN

Composite system	Test Angle	Sample #	Thickness average mm	Width average mm	Vf %	Area-average Mm2	Yield force N	Yield stress N/mm2
Cotton/semi-IPN	0°	C0/1	0.42	25.17	0.40	10.64	100	9.4
Cotton/semi-IPN	0°	C0/2	0.46	24.92	0.22	11.34	150	13.2
Cotton/semi-IPN	0°	C0/3	0.42	25.01	0.23	10.44	150	14.4
Cotton/semi-IPN	0°	C0/4	0.44	24.91	0.22	10.96	150	13.7
Cotton/semi-IPN	0°	C0/5	0.43	25.17	0.22	10.70	150	14.0
Cotton/semi-IPN	0°	C0/6	0.39	24.89	0.22	9.71	150	15.5
Cotton/semi-IPN	0°	C0/7	0.40	25.17	0.22	10.01	150	15.0
Averages					**0.25**			**13**
Cotton/semi-IPN	22.5°	C22.5/1	0.56	25.00	0.13	13.88	150	10.8
Cotton/semi-IPN	22.5°	C22.5/2	0.45	25.13	0.17	11.41	150	13.1
Cotton/semi-IPN	22.5°	C22.5/3	0.48	25.07	0.19	12.09	140	11.6
Cotton/semi-IPN	22.5°	C22.5/4	0.48	25.05	0.20	11.90	130	10.9
Cotton/semi-IPN	22.5°	C22.5/5	0.51	25.09	0.20	12.67	140	11.0
Cotton/semi-IPN	22.5°	C22.5/6	0.42	25.09	0.20	10.48	140	13.4
Cotton/semi-IPN	22.5°	C22.5/7	0.42	24.68	0.19	10.30	140	13.6
Averages					**0.18**			**12**
Cotton/semi-IPN	45°	C45/1	0.44	24.95	0.17	10.92	110	10.1
Cotton/semi-IPN	45°	C45/2	0.40	24.95	0.20	10.04	140	13.9
Cotton/semi-IPN	45°	C45/3	0.41	25.34	0.20	10.32	130	12.6
Cotton/semi-IPN	45°	C45/4	0.48	24.88	0.20	11.82	110	9.3
Cotton/semi-IPN	45°	C45/5	0.41	25.10	0.20	10.16	120	11.8
Cotton/semi-IPN	45°	C45/6	0.43	25.17	0.20	10.76	130	12.1
Cotton/semi-IPN	45°	C45/7	0.42	24.71	0.20	10.38	100	9.6
Averages					**0.20**			**11**

Table 4.10 Yield stress for glass-reinforced semi-IPN

Composite system	Test Angle	Sample #	Thickness average mm	Width average mm	Vf %	Area-average mm2	Yield force N	Yield stress N/mm2
Glass/semi-IPN	0°	G0/1	0.17	25.04	0.32	4.32	760	176.0
Glass/semi-IPN	0°	G0/2	0.16	24.62	0.32	4.00	755	188.7
Glass/semi-IPN	0°	G0/3	0.15	25.04	0.36	3.76	860	229.0
Glass/semi-IPN	0°	G0/4	0.17	25.14	0.33	4.34	720	166.0
Glass/semi-IPN	0°	G0/5	0.16	25.12	0.31	3.96	780	197.1
Glass/semi-IPN	0°	G0/6	0.16	25.09	0.32	4.01	840	209.2
Glass/semi-IPN	0°	G0/7	0.17	25.00	0.31	4.19	730	174.3
Averages					**0.32**			**191**
Glass/semi-IPN	22.5°	G22.5/1	0.15	25.42	0.39	3.69	40	10.9
Glass/semi-IPN	22.5°	G22.5/2	0.14	25.88	0.47	3.49	40	11.4
Glass/semi-IPN	22.5°	G22.5/3	0.14	25.04	0.44	3.38	50	14.8
Glass/semi-IPN	22.5°	G22.5/4	0.14	24.89	0.41	3.42	80	23.4
Glass/semi-IPN	22.5°	G22.5/5	0.15	24.71	0.43	3.71	40	10.8
Glass/semi-IPN	22.5°	G22.5/6	0.14	25.06	0.42	3.57	30	8.4
Glass/semi-IPN	22.5°	G22.5/7	0.15	25.19	0.42	3.72	30	8.1
Averages					**0.43**			**12**
Glass/semi-IPN	22.5°	G'22.5/1	0.44	24.87	0.11	10.88	450	41.4
Glass/semi-IPN	22.5°	G'22.5/2	0.43	24.89	0.11	10.64	450	42.3
Glass/semi-IPN	22.5°	G'22.5/3	0.44	25.03	0.10	11.07	620	56.0
Glass/semi-IPN	22.5°	G'22.5/4	0.68	24.62	0.09	16.74	680	40.6
Glass/semi-IPN	22.5°	G'22.5/5	0.49	25.17	0.10	12.21		0.0
Glass/semi-IPN	22.5°	G'22.5/6	0.52	25.19	0.10	13.16	840	63.8
Glass/semi-IPN	22.5°	G'22.5/7	0.49	25.17	0.10	12.33		0.0
Averages					**0.10**			**48**
Glass/semi-IPN	45°	G45/1	0.16	24.96	0.31	3.87	20	5.2
Glass/semi-IPN	45°	G45/2	0.15	25.02	0.33	3.75	40	10.7
Glass/semi-IPN	45°	G45/3	0.16	25.10	0.36	3.95	60	15.2
Glass/semi-IPN	45°	G45/4	0.14	25.10	0.38	3.45	50	14.5
Glass/semi-IPN	45°	G45/5	0.16	25.07	0.39	3.89	50	12.9
Glass/semi-IPN	45°	G45/6	0.14	24.70	0.39	3.52	40	11.4
Glass/semi-IPN	45°	G45/7	0.15	24.87	0.35	3.79	50	13.2
Averages					**0.36**			**11**
Glass/semi-IPN	45°	G'45/1	0.50	24.88	0.10	12.31	250	20.3
Glass/semi-IPN	45°	G'45/2	0.44	25.22	0.13	11.10	160	14.4
Glass/semi-IPN	45°	G'45/3	0.50	25.20	0.10	12.66	200	15.8
Glass/semi-IPN	45°	G'45/4	0.41	24.89	0.12	10.14	220	21.7
Glass/semi-IPN	45°	G'45/5	0.51	25.08	0.09	12.67	200	15.8
Glass/semi-IPN	45°	G'45/6	0.55	25.10	0.09	13.87	300	21.6
Glass/semi-IPN	45°	G'45/7	0.45	24.80	0.11	11.16	200	17.9
					0.11			**18**

Table 4.11 Yield stress for Kevlar-reinforced semi-IPN

Composite system	Test Angle	Sample #	Thickness average mm	Width average mm	Vf %	A-average Mm2	Yield force N	Yield stress N/mm2
Kevlar/semi-IPN	0°	KO/1	0.14	24.73	0.36	3.34	1000	299.5
Kevlar/semi-IPN	0°	KO/2	0.14	24.96	0.36	3.49	1050	300.5
Kevlar/semi-IPN	0°	KO/3	0.16	24.91	0.37	3.92	1200	305.9
Kevlar/semi-IPN	0°	KO/4	0.16	24.85	0.37	3.85	1040	270.0
Kevlar/semi-IPN	0°	KO/5	0.15	24.87	0.40	3.61	1120	310.6
Kevlar/semi-IPN	0°	KO/6	0.15	25.58	0.39	3.71	1020	275.0
Kevlar/semi-IPN	0°	KO/7	0.15	24.82	0.36	3.79	1040	274.8
Averages					**0.38**			**290**
Kevlar/semi-IPN	22.5°	K22.5/1	0.15	25.04	0.40	3.82	95	26.2
Kevlar/semi-IPN	22.5°	K22.5/2	0.16	24.69	0.39	3.95	95	38.0
Kevlar/semi-IPN	22.5°	K22.5/3	0.14	24.90	0.34	3.49	120	43.0
Kevlar/semi-IPN	22.5°	K22.5/4	0.15	25.03	0.34	3.82	95	39.3
Kevlar/semi-IPN	22.5°	K22.5/5	0.28	25.20	0.36	6.99	100	21.4
Kevlar/semi-IPN	22.5°	K22.5/6	0.13	24.98	0.39	3.31	75	45.3
Kevlar/semi-IPN	22.5°	K22.5/7	0.13	25.04	0.42	3.19	95	47.0
Averages					**0.38**			**37**
Kevlar/semi-IPN	45°	K45/1	0.18	25.22	0.27	4.41	90	21.5
Kevlar/semi-IPN	45°	K45/2	0.22	24.72	0.21	5.44	130	17.5
Kevlar/semi-IPN	45°	K45/3	0.18	24.79	0.27	4.34	170	27.7
Kevlar/semi-IPN	45°	K45/4	0.19	25.11	0.23	4.71	200	20.2
Kevlar/semi-IPN	45°	K45/5	0.18	24.84	0.29	4.47	150	22.4
Kevlar/semi-IPN	45°	K45/6	0.18	25.19	0.24	4.53	190	16.5
Kevlar/semi-IPN	45°	K45/7	0.15	25.19	0.29	3.72	130	25.6
Averages					**0.26**			**21**

Discussion

Non-reinforced Samples

The modulus of elasticity for normal rigid PVC is between 2.41 and 4.14 GPa. The normal yield strength for the same material is about 40.7 to 44.8 MPa [Callister, 2000]. These values are above the elastic modulus of 2.5 GPa (at +25°C) and yield strength of 25 MPa obtained for the semi-IPN based on PVC and reactive plasticizer tested above. Also, the glass transition temperature of rigid PVC is about 80 °C [Callister, 2000] while the major transition region for the semi-IPN tested above is located at approximately 50 °C. Several reasons exist that can explain these results. Tensile strength (σ), modulus of elasticity (E), and glass transition temperature (Tg) of composite systems can be predicted by means of the simple rule of mixtures (ROM) as provided in equations 4.1 [Callister, 2000].

$$P_c = \Sigma P_x V_x \qquad \text{(equation 4.1)}$$

In which

P_c Property of the multiphase system (σ, E, or Tg)
P_x Property of phase x
V_x Volume fraction of phase x

According to the rule of mixture (ROM), the properties of composite systems can be calculated by summation of the properties of each individual phase times the volume fraction of that phase present in the system. According to the ROM, low values for modulus, yield strength, and glass transition temperature for the semi-IPN can thus be explained. Incomplete conversion of reactive plasticizer into rigid polymer will leave a significant volume fraction of un-reacted reactive plasticizer present in the cured semi-

IPN. Together with the epoxidized linseed oil (which also act as plasticizer), this uncured reactive plasticizer will decrease overall mechanical and thermal properties of the semi-IPN. The semi-IPN approximately contains a volume fraction of 0.47 of PVC, 0.426 of reactive plasticizer, and 0.103 of epoxidized linseed oil. Assuming following properties for each of the different phases:

PVC	$E \approx 3.2$ GPa	$\sigma \approx 40$ MPa	$Tg \approx 80$ °C
Fully cured Reactive Plasticizer	$E \approx 3$ GPa	$\sigma \approx 30$ MPa	$Tg \approx 60$ °C
Epoxidized Linseed oil	$E \approx 0$ GPa	$\sigma \approx 0$ MPa	$Tg \approx 0$ °C

And knowing the properties of the cured semi-IPN:

Semi-IPN	$E \approx 2.5$ GPa	$\sigma \approx 25$ MPa	$Tg \approx 50$ °C

One can estimate the volume fraction of reactive plasticizer that is contributing to the strength of the composite system (X) by applying the ROM. From these values one can calculate the percentage of reactive plasticizer that is actually working at full potential:

Tg $(0.47 * 80°C) + (X * 60°C) + (0.103 * 0°C) = 50°C$
$\Rightarrow X \approx 0.206$ (Volume fraction reactive plasticizer)
Exact volume fraction reactive plasticizer = 0.426
Percent of potential ≈ 0.48%

E $(0.47 * 3.2\ GPa) + (X * 3GPa) + (0.103 * 0GPa) = 2.5\ GPa$
$\Rightarrow X \approx 0.33$ (Volume fraction reactive plasticizer)
Exact volume fraction reactive plasticizer = 0.426
Percent of potential ≈ 0.78%

σ $(0.47 * 40\ MPa) + (X * 30\ MPa) + (0.103 * 0\ MPa) = 25MPa$
$\Rightarrow X \approx 0.206$ (Volume fraction reactive plasticizer)
Exact volume fraction reactive plasticizer = 0.426
Percent of potential ≈ 0.48%

Assuming full extend of cure, properties for the semi-IPN should thus be:

Tg	(0.47 * 80°C) + (0.426 * 60°C) + (0.103 * 0°C) = 63 °C
E	(0.47 * 3.2 GPa) + (0.426 * 3GPa) + (0.103 * 0GPa) = 2.78 GPa
σ	(0.47 * 40 MPa) + (0.426 * 30 MPa) + (0.103 * 0 MPa) = 31.5 MPa

Results for modulus, yield strength, and glass transition temperature indicate that the UV-cured reactive plasticizer is only performing at approximately 47 to 78 percent of it's full potential. It can be concluded therefore that cross-link efficiency for the UV cured system is very moderate. Results obtained from the dynamic mechanical tests confirm this conclusion. Elastic modulus for example starts to decrease even at a very low temperature-increase and no clear plateau is present below the glass transition temperature. (figures 4.11 through 4.19). Possible explanations for these results are the absorption of UV-light by the epoxidized linseed oil (causing inefficient decomposition of photo-initiator) and the thickness of the samples (due to limited penetration depth of UV-light).

Fiber-reinforced Samples

The longitudinal tensile strength of fiber-reinforced polymer composites can also be predicted by the ROM as provided in equations 4.2 [Callister, 2000].

$$\sigma_{cl} = \sigma'_m(1-V_f) + \sigma^* V_f \qquad \text{(equation 4.2)}$$

In which

σ_{cl} is the longitudinal strength of a fiber reinforced composite (N/mm^2)
σ'_m is the stress in the matrix at fiber failure (N/mm^2)
σ^* is the fiber tensile strength (N/mm^2)
V_f is the fiber volume fraction (%)

According to the ROM, the tensile strength of a fiber-reinforced polymer composite increases with increased fiber volume fraction. Results however indicate the opposite. This can be explained by the fact that laminas tested were very thin. The fiber reinforcement used consisted of plain weave fabrics of about 0.10 to 0.15 mm thickness. The thinnest samples (containing the highest volume fractions of fiber) were thus only slightly coated with the matrix. In addition to this, the coating may not have been fully uniform in thickness. Transfer of stress under these conditions can only occur through the matrix present in-between adjacent fibers. This explains why samples with higher fiber volume fraction performed less than those with lower volume fraction. The latter embedded the fibers more fully thus providing more efficient transfer of stress (figure 4.20). In addition to this, inefficient cure through obstruction of UV-ligh by the various fibers may also have resulted in a lesser extend of cure for the semi-IPN. Because of this, optimum matrix properties may not have been accomplished.

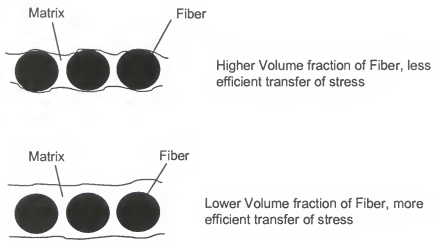

Matrix
Fiber
Higher Volume fraction of Fiber, less efficient transfer of stress
Matrix
Fiber
Lower Volume fraction of Fiber, more efficient transfer of stress

Figure 4.20 Lower and higher fiber volume fraction

CHAPTER 5
STRUCTURAL ANALYSIS OF AN RPC STRUCTURE

The principle behind RPC construction is to accomplish a material for which the modulus of elasticity increases significantly at a distinct point in time. Previous chapters covered the listing of possible RPC material solutions to accomplish this objective. An experimental section was also included in which the basic mechanical properties for one specific material were determined. Although we know that an increase in modulus of elasticity is needed to make the RPC concept work, so far this level of increase has not been quantified. The purpose of this chapter is therefore to establish a better understanding on what kind of mechanical materials properties are feasible for use in RPC structures.

Scope and Objectives

The magnitude of stress encountered in any structural design depends on design configuration, material properties, and the magnitude of externally applied loads. Since an infinite number of possible design configuration exist, a wide range of material properties can be established that might perform well for each conceivable design. The scope of this study was therefore limited to the analysis of one design only, being a simple prismatic building 7m (≈24 feet) wide, 14m (≈48 feet) long, and with a ceiling height of 2.4m (≈8 feet). This shape represented the enclosing envelope of a conventional single-family house in its most basic form. The objective of the structural analysis provided in this chapter is to establish a better understanding of the stresses and deformations that exist in a rigid thin membrane structures, for a given structural design and normal loading conditions.

Methods

First, a structural system was proposed for the simple prismatic design. Second, one simple load-case was considered composed of both horizontal and vertical uniform distributed loads acting upon the walls and roof of this structure. Third, material properties were assumed that are typical for fiber reinforced polymer matrix systems. Fourth, a general finite element (FEM) program for structural analysis (SSTAN) was used to model and analyze parts of this structure. Stresses and deflection throughout the structure were calculated by the FEM program and were used to evaluate the proposed design to the design criteria. From this evaluation, recommendations could be made to alter either the structural design or material properties. Figure 5.1 illustrates this methodology.

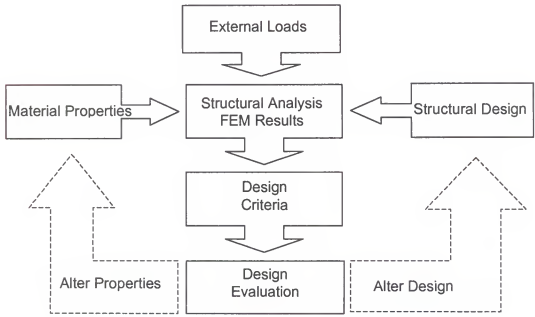


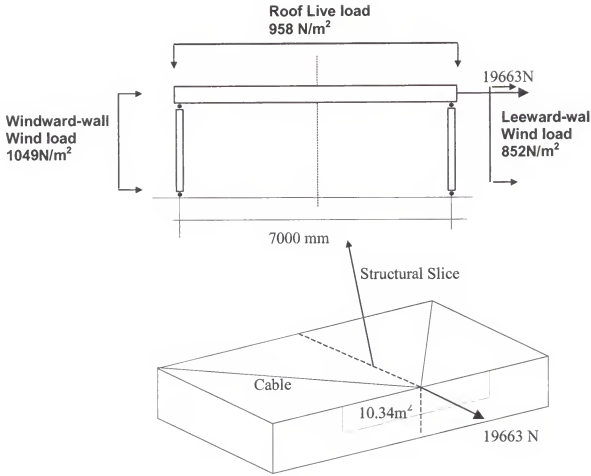
Figure 5.1 Methodology Structural Analysis of an RPC structure

Structural Design

Figure 5.2 provides an isometric view, section, and detail of an RPC construction placed on a concrete slab on grade. An RPC wall composed of tubular rectangular column-elements 0.2m wide and 0.2 meter deep is envisioned. The roof structure consists of a series of beams with rectangular cross-section 0.2m wide and 0.4m high. The interior ceiling height is 2.4 m (8 feet). A membrane thickness of 0.4 mm was selected for both roof and walls elements. Each beam and column element only supports those loads that apply directly to its own exterior surface (web). The connection between roof beams and columns, and columns and foundation, were modeled as hinges. Lateral stability was provided by means of a cable-system that connects the top of the middle column with the opposite top of the side walls (Figure 5.2). Cables were considered to have relatively high modulus of elasticity and have a cross sectional area of 25 mm^2.

Assumptions

Buildings need to be designed to sustain a combination of loads including dead loads, live loads, snow loads, and wind loads. The magnitude of these loads depends on location and type of construction and is often regulated by local, national, or international building codes. For the structural analysis provided in this chapter, a hypothetical building-site, located in a tropical climate with open terrain topography and wind speeds as strong as 130 mph was selected. The International Building Code (2000) was used to determine the structural loads that apply for similar location in the United States. A site on the East coast of central Florida was selected as representative for the hypothetical location described above.



$(7.31\text{m} \times 2.83\text{ m})/2 = 10.34\ \text{m}^2$

$10.34\ \text{m}^2 \times (1049\text{N} + 852\text{N}) = 19663\text{N}$

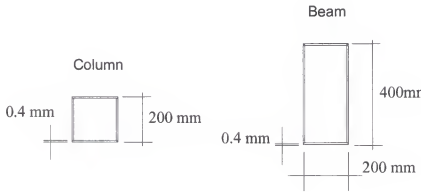


Figure 5.2 Section and Cross section Beam & Column RPC structure

External Loads

Dead Loads

Dead loads are composed of the weight of all materials of construction incorporated into the building, including but not limited to walls, floors, roofs, ceilings, and fixed service equipment. Since RPC structures are extremely lightweight, no dead loads were considered for the structural analysis.

Live Loads

Live loads are those loads produced by the occupancy of the building or structure, not including construction loads or environmental loads. The only live loads considered in the structural analysis of the RPC structure were those that apply to the roof of the structure as a result of maintenance by workers, equipment and materials. For flat roofs with a tributary loaded area of less than 200 square feet, the minimum roof live load is 20 pounds per square foot or 958 Pa according to the international building code. Live loads apply directly to the surfaces of the beam elements and are modeled as such for the FEM analysis

Snow Loads

No snow loads apply for the coastal regions of Central Florida.

Wind load

Wind loads are the pressures on buildings or structures in pounds per square foot (or Pa) due to wind blowing in any direction. The design pressure depends on specific site location and exposure category. Exposure category C (open terrain with scattered obstructions having heights less than 9.15 m) was used to calculate the design wind pressures. The simplified provision for low-rise buildings was used to determine the leeward and windward wall pressures for the design under consideration (International Building Code, section 1609.6). For the main wind-force resisting system (MWFRS), vertical and horizontal loads based on the combined leeward and windward wall

pressures were determined from the tables provided in the international building code. No upward wind load for the roof was included in the analysis; the roof live load was used instead. All wind loads were assumed to apply to the interior zones of the building. Table 5.1 provides the results for the various design wind loads. Wind loads apply directly to the surfaces of the column elements and were does modeled as such for the FEM analysis. In addition to this, part of the wind loads that apply to the complete windward and leeward wall needed to be transferred to the side-walls via the cable system embedded in the roof. A concentrated load was therefore placed on the FEM model to represent this load as illustrated in figure 5.2.

Table 5.1 Design Wind Loads for walls and roof.

Wall	Basic Wind Speed (mph)	MWFRS loads* (psf)	Height and Exposure Adjustment Coefficient (Exposure C)	Importance Factor	Design wind load (psf)	Design wind load (Pa)
Windward	130	14.9	1.47	1	21.9	1049
Leeward	130	-12.1	1.47	1	-17.8	-852

* For a building with mean roof height of 30 feet located in exposure B

Material Properties

Typical properties for an E-Glass continuous fiber reinforced (Vf=0.6) epoxy matrix are 45 GPa and 12 GPa for longitudinal and transverse modulus of elasticity The yield strength for the same material is about 1020 MPa in the longitudinal and 40 MPa in the transverse direction [Callister, 2000]. The properties of fiber-reinforced materials thus strongly depend on the direction at which the load is applied. Upon careful design however, a material can be made for which properties are quasi isotropic in one plane.

Examples of this are quasi-isotropic laminates and random oriented discontinuous fiber lamina. The isotropic properties for such laminated materials can further be calculated using lamination theory [Mallick, 1993]. For example, un-reinforced polycarbonate has a tensile strength of about 60MPa and a modulus of elasticity of 2.3 GPa. The addition of 30 % by volume of randomly oriented glass fibers increases these properties to 131MPa and 8.62 GPa respectively [Callister, 2000]. For the structural analysis provided in this chapter, isotropic material behavior was assumed in order to simplify the analysis. An isotropic material having a modulus of elasticity of 8.5 GPa, and a poison's ratio of 0.3 was selected. This material was assumed to consist of the semi-IPN matrix based on PVC and reactive plasticizer (see chapter 4) containing a volume fraction of 30 % of randomly oriented discontinuous glass fibers. The cables that provide lateral stability were considered to have a relative high modulus of elasticity of 131Gpa (aramid) and a cross sectional area of 25mm^2.

Design Criteria

Allowable Stress

The Allowable Stress Design method was used to evaluate the results of the FEM structural analysis. The elastic stresses in the structural members due to the maximum expected loads were calculated. From these, maximum allowable stresses could be determined. The allowable stress was set equal to the yield (or failure) stress of the material divided by a safety factor. A conservative safety factor of two (half the yield stress) was adopted.

Deflection Roof

According to the international building code, the total allowable deflection for structural roofing and siding made of formed metal sheets is L/60. The code further stipulates that a roof deflection of L/140 is adequate for roofs without interior ceiling materials attached to it. (International Building Code 2000, section 1604.3.1).

FEM Analysis

SSTAN, FEM Program

SSTAN, a Simple Structural Analysis Program using finite elements for static load analysis of three-dimensional structural systems was used to analyze the RPC-structure. SSTAN is a batch program for which the structural information is contained in a file named "INPUT". Once the input file is ready, the program processes the information and places results into a file named "OUTPUT" [Hoit, 1995]. SSTAN has the additional capability of plotting stress, moment, and displacement contours for the elements. This allows for visual inspection of stresses, moments, and displacements. The following information is contained within the input file: 1) Node coordinates, 2) Node boundary conditions, 3) Node connectivity 4) Uniform loads applied to each element.

FEM Model

Only a selected part of the structure was modeled and analyzed, this consisted of a slice of one "structural element" through the building as illustrated in figure 5.2. As described above, the connections between roof beams and columns, and columns and foundation, were modeled as hinges. Lateral stability was provided by means of a cable-system (Figure 5.2). The cables were modeled to only take tensile stress. Both roof beams and columns were modeled as beam elements. Moments of inertia were calculated according to equation 5.1. SSTAN has the option to place uniform loads directly to the elements, therefore, no equivalent nodal loads needed to be calculated. All loads were placed directly to the appropriate beam or columns. The uniformly distributed loads (UDL) that apply to each element were multiplied by two to correctly model the true loading condition, according to figure 5.4. The UDL was further multiplied by 200mm (width of beam or column), to transfer from N/mm^2 to N/mm. The uniform load for the roof for example is thus the roof life load: $0.000958N/mm^2 \times 2 \times 200mm = 0.3832$

N/mm. Figure 5.3 provides node and element numbering. The SSTAN input file is provided on page 92.

$$I y = (BH^3 - bh^3) / 12 \qquad \text{(equation 5.1)}$$

Were:
H = Column or beam height
h = Column or beam interior height
B = Column or beam width
b = Column or beam interior width

Assumptions

The effects of highly concentrated loads acting upon the thin membrane structure were not considered. The assumption was further made that local buckling of beam or column membranes is prevented by means of a cavity filling composed of a loose fill insulation material.

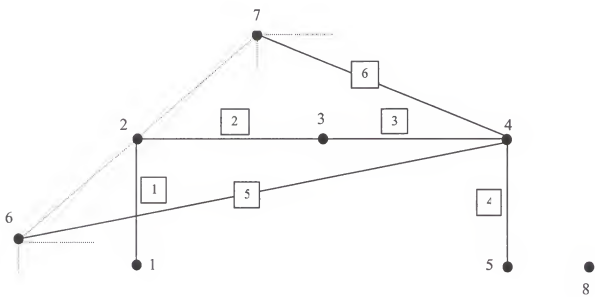


Figure 5.3 FEM Model, node and element numbering

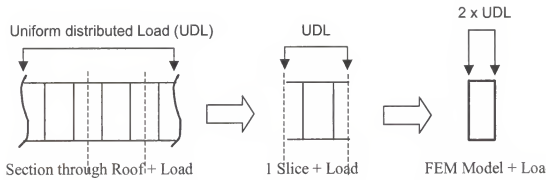


Figure 5.4 FEM Model Load condition

SSTAN input file:

```
RPC Frame using beam element for analysis
8,2,1,P=1, C=1
:
COORDINATES
1 x=0 y=0 z=0
2 x=0 y=2600 z=0
3 x=3500 y=2600 z=0
4 x=7000 y=2600 z=0
5 x=7000 y=0 z=0
6 x=0 y=2600 z=-7000
7 x=0 y=2600 z=7000
8 x=10000 y=0 z=0
:
BOUNDARY
1 DOF=F,F,F,F,F,R : Node 1
2 DOF=R,R,F,F,F,R: Node 2
3 DOF=R,R,F,F,F,F: Node 3
4 DOF=R,R,F,F,F,R: Node 4
5 DOF=F,F,F,F,F,R : Node 5
6 DOF=F,F,F,F,F,R : Node 6
7 DOF=F,F,F,F,F,R : Node 7
8 DOF=F,F,F,F,F,R : Node 8
:
BEAM
4,2
1 I=2120567 A=320 E= 8500          : Member properties
2 I=10628326 A=480 E= 8500         : Member properties
1 1,2,8 M=1 L=-0.4116 p=3 :Element 1 Column 200x200x0.4 uniform load 0.41N/mm
2 2,3,8 M=2 L=-0.3832 p=1 :Element 2 Beam 200x400x0.4 uniform load 0.38 N/mm
3 3,4,8 M=2 L=-0.3832 p=2 :Element 3 Beam 200x400x0.4 uniform load 0.38 N/mm
4 4,5,8 M=1 L=-0.3408 p=3 :Element 3 Beam 200x200x0.4 uniform load 0.34 N/mm
:
TRUSS
2,1
1 A=25 E=131000                    : Member properties
5 4,6 M=1 C=1                      : Tension member between node 4 and 6
6 4,7 M=1 C=1                      : Tension member between node 4 and 7
:
LOADS
4 L=1 F=19663                      : Concentrated load of 19663N
:
```

Results structural Analysis

This section provides results for stresses and deflections throughout the RPC structure as calculated by the SSTAN FEM-program. The complete SSTAN output file is provided below:

SSTAN Output File:

```
      ******************************************************
            SSTAN  -  Simple Structural Analysis Program
      Copyright 1995  By  Dr. Marc Hoit, University of Florida
      File Compression and Equation Parser By Dr. G Consolazio
             Nodal Renumbering using the PFM algorithm
                   Static and Dynamic Version
                 Version 5.48     August 16, 2000
      ******************************************************

           *** NON-LINEAR SOLUTION ***

Input File = "C:\My Documents\dissertation\Sstan\SSTANbeam8.txt"
Analysis Run on 11-21-2000 at 10:23


RPC Frame using beam element for analysis
NUMBER OF JOINTS                        = 8
NUMBER OF DIFFERENT ELEMENT TYPES       = 2
NUMBER OF LOAD CONDITIONS               = 1
NUMBER OF LOAD COMBINATIONS             = 0
TOLERANCE FOR NONLINEAR SOLUTION        = 0.10000E-01
Truss has Non-Compression/Tension       = YES
Frames/Beams Include P-Delta Effects    = YES
Sequential Loads Active                 = NO

NODE    BOUNDARY CONDITION CODES            NODAL POINT COORDINATES
NUMBER  X    Y    Z   XX   YY   ZZ          X          Y          Z
   1    F    F    F    F    F    R       0.00       0.00       0.000
   2    R    R    F    F    F    R       0.00    2600.00       0.000
   3    R    R    F    F    F    F    3500.00    2600.00       0.000
   4    R    R    F    F    F    R    7000.00    2600.00       0.000
   5    F    F    F    F    F    R    7000.00       0.00       0.000
   6    F    F    F    F    F    R       0.00    2600.00   -7000.000
   7    F    F    F    F    F    R       0.00    2600.00    7000.000
   8    F    F    F    F    F    R   10000.00       0.00       0.000
```

SSTAN Output File Continued:

```
EQUATION NUMBERS
    N     X     Y     Z    XX    YY    ZZ
    1     0     0     0     0     0     1
    2     2     3     0     0     0     4
    3     5     6     0     0     0     0
    4     7     8     0     0     0     9
    5     0     0     0     0     0    10
    6     0     0     0     0     0    11
    7     0     0     0     0     0    12
    8     0     0     0     0     0    13

 ***** TRUSS MEMBERS *****

 NUMBER OF DIFFERENT MEMBER PROPERTIES = 1

 MEMBER PROPERTY NUMBER--= 1
 AXIAL AREA-------------= 25.00
 MODULUS OF ELASTICITY, E= 0.1310E+06

 *** ZC or ZT in T/C column means Zero compression or Tension ***
 MEMB  CONNECT.  CASE  MAT                    END ECCENTRICITIES
 NUM.            ACTV  SET  *****  I-END     ****  J-END    ***** ZERO
    I    J                 X-VAL Y-VAL Z-VAL X-VAL Y-VAL Z-VAL  T/C
5    4    6    1     1     0.00   0.00   0.00  0.00  0.00  0.00  ZC
 INITIAL TENSION = 0.000
6    4    7    1     1     0.00   0.00   0.00   0.00 0.00  0.00  ZC
 INITIAL TENSION = 0.000
  The total volume of the truss elements = 494974.746830583258998

 ***** FRAME MEMBERS *****

 NUMBER OF MEMBER PROPERTIES = 2

 MEMBER PROPERTY NUMBER --------- = 1
 AXIAL AREA, A ------------------ = 320.000
 SHEAR AREA, 3 Axis ------------- = 0.000000
 SHEAR AREA, 2 Axis ------------- = 0.000000
 TORSIONAL MOMENT OF INERTIA, J   = 0.000000
 MOMENT OF INERTIA, I(2) -------- = 0.212057E+07
 MOMENT OF INERTIA, I(3) -------- = 0.000000
 MODULUS OF ELASTICITY, E ------- = 8500.00
 SHEAR MODULUS, G --------------- = 3269.23     (USED FOR JG/L CAL.)
 MASS / UNIT LENGTH (for dynamics)= 0.000000

 MEMBER PROPERTY NUMBER --------- = 2
 AXIAL AREA, A ------------------ = 480.000
 SHEAR AREA, 3 Axis ------------- = 0.000000
 SHEAR AREA, 2 Axis ------------- = 0.000000
 TORSIONAL MOMENT OF INERTIA, J   = 0.000000
 MOMENT OF INERTIA, I(2) -------- = 0.106283E+08
 MOMENT OF INERTIA, I(3) -------- = 0.000000
 MODULUS OF ELASTICITY, E ------- = 8500.00
 SHEAR MODULUS, G --------------- = 3269.23     (USED FOR JG/L CAL.)
 MASS / UNIT LENGTH (for dynamics)= 0.000000
```

SSTAN Output File Continued:

```
MEMB   CONNECTIVITY  MATERIAL                    END ECCENTRICITIES
NUM. K=0 FOR Z-AXIS    SET  ***** I-END     ****   J-END     *****  PIN
       I    J    K          X-VAL Y-VAL Z-VAL X-VAL Y-VAL Z-VAL   OPT
  1    1    2    8     1    0.00  0.00  0.00  0.00  0.00  0.00   3
UNIFORM LOAD = -0.412
  2    2    3    8     2    0.00  0.00  0.00  0.00  0.00  0.00   1
UNIFORM LOAD = -0.383
  3    3    4    8     2    0.00  0.00  0.00  0.00  0.00  0.00   2
UNIFORM LOAD = -0.383
  4    4    5    8     1    0.00  0.00  0.00  0.00  0.00  0.00   3
UNIFORM LOAD = -0.341
  The total volume of the beam elements = 5024000.000000000000000

THE NODE NUMBERING USED PRODUCED A HALF BANDWIDTH OF    3

TOTAL STORAGE REQUIRED  = 224
TOTAL STORAGE AVAILABLE = 1350000

*** CONCENTRATED NODAL LOADS ***
 NODE   LOAD     X          Y          Z          XX         YY         ZZ
  4       1  0.20E+05   0.00E+00   0.00E+00   0.00E+00   0.00E+00   0.00E+00

EQUATION #    4 DIAGONAL TERM =  0.0000000E+00
EQUATION #    9 DIAGONAL TERM =  0.0000000E+00
EQUATION #   10 DIAGONAL TERM =  0.0000000E+00
EQUATION #   11 DIAGONAL TERM =  0.0000000E+00
EQUATION #   12 DIAGONAL TERM =  0.0000000E+00
EQUATION #    4 DIAGONAL TERM =  0.0000000E+00
EQUATION #    9 DIAGONAL TERM =  0.0000000E+00
EQUATION #   10 DIAGONAL TERM =  0.0000000E+00
EQUATION #   11 DIAGONAL TERM =  0.0000000E+00
EQUATION #   12 DIAGONAL TERM =  0.0000000E+00
EQUATION #    4 DIAGONAL TERM =  0.0000000E+00
EQUATION #    9 DIAGONAL TERM =  0.0000000E+00
EQUATION #   10 DIAGONAL TERM =  0.0000000E+00
EQUATION #   11 DIAGONAL TERM =  0.0000000E+00
EQUATION #   12 DIAGONAL TERM =  0.0000000E+00

SOLUTION CONVERGED IN   3 ITERATION(S)

*** PRINT OF FINAL DISPLACEMENTS ***
DISPLACEMENTS FOR LOAD CONDITION  1
NODE    X           Y           Z           XX          YY          ZZ
1 0.00000E+00 0.00000E+00 0.00000E+00 0.0000E+00 0.0000E+00 0.00000E+00
2 0.63564E+02-0.12820E+01 0.00000E+00 0.0000E+00 0.0000E+00 0.00000E+00
3 0.63077E+02-0.13738E+03 0.00000E+00 0.0000E+00 0.0000E+00 0.00000E+00
4 0.62590E+02-0.12820E+01 0.00000E+00 0.0000E+00 0.0000E+00 0.00000E+00
5 0.00000E+00 0.00000E+00 0.00000E+00 0.0000E+00 0.0000E+00 0.00000E+00
6 0.00000E+00 0.00000E+00 0.00000E+00 0.0000E+00 0.0000E+00 0.00000E+00
7 0.00000E+00 0.00000E+00 0.00000E+00 0.0000E+00 0.0000E+00 0.00000E+00
8 0.00000E+00 0.00000E+00 0.00000E+00 0.0000E+00 0.0000E+00 0.00000E+00
```

SSTAN Output File Continued:

```
 ---------------- FORCE'S TRUSS MEMBERS --------------
 ASTERISK (*C or *T) MEANS COMPRESSION OR TENSION SET TO ZERO FOR THIS
MEMBER
 ASTERISK (*SQ) MEANS SEQUENCED MEMBER AND NOT ACTIVE
 MEMBER   LOAD   IEND   JEND       AXIAL          AXIAL
   #      #      #      #          FORCES         STRESS
   5      1      4      6      14641.4914       585.6597
   6      1      4      7      14641.4914       585.6597


       ---------------------- FRAME MEMBER RESULTS ----------------
  MEM LOAD NODE            1-2 PLANE                1-3 PLANE        AXIAL
FORCE
  #    #    #       MOMENT        SHEAR       MOMENT        SHEAR
  1    1    1 0.0000E+00 0.0000E+00 0.0000E+00-0.50229E+03 0.13412E+04
            2 0.0000E+00 0.0000E+00 0.00000E+00-0.56787E+03-0.13412E+04
                                          AXIAL TORQUE =  0.00000E+00
**MAXIMUM MIDSPAN MOMENT=-0.348E+06 AT DISTANCE  1300.0 FROM NODE     1
  2    1    2 0.0000E+00 0.0000E+00 0.0000E+00-0.13412E+04 0.56787E+03
            3 0.0000E+00 0.0000E+00 0.24244E+07-0.36948E-12-0.56787E+03
                                          AXIAL TORQUE =  0.00000E+00
  3    1    3 0.0000E+00 0.0000E+00-0.24244E+07 0.19895E-12 0.56787E+03
            4 0.0000E+00 0.0000E+00 0.00000E+00-0.13412E+04-0.56787E+03
                                          AXIAL TORQUE =  0.00000E+00
  4    1    4 0.0000E+00 0.0000E+00 0.00000E+00-0.47533E+03 0.13412E+04
            5 0.0000E+00 0.0000E+00 0.00000E+00-0.41075E+03-0.13412E+04
                                          AXIAL TORQUE =  0.00000E+00
**MAXIMUM MIDSPAN MOMENT=-0.288E+06 AT DISTANCE  1300.0 FROM NODE     4

 REACTIONS FOR LOAD CONDITION  1
 NODE       X            Y            Z            MX           MY           MZ
 1 0.32789E+02 0.13412E+04 0.0000E+00 0.00000E+00 0.0000E+00 0.0000E+00
 2 0.53508E+03-0.50295E+03 0.0000E+00 0.00000E+00 0.0000E+00 0.0000E+00
 3 0.00000E+00-0.16765E+04 0.0000E+00 0.00000E+00 0.0000E+00 0.0000E+00
 4 0.20106E+05-0.50295E+03 0.0000E+00 0.00000E+00 0.0000E+00 0.0000E+00
 5 0.32287E+02 0.13412E+04 0.0000E+00 0.00000E+00 0.0000E+00 0.0000E+00
 6-0.10353E+05 0.00000E+00-0.10353E+05 0.0000E+00 0.0000E+00 0.0000E+00
 7-0.10353E+05 0.00000E+00 0.10353E+05 0.0000E+00 0.0000E+00 0.0000E+00
 8 0.00000E+00 0.00000E+00 0.0000E+00 0.00000E+00 0.0000E+00 0.0000E+00
```

Summary Results

A summary of the various stresses and deflections throughout the RPC structure as calculated by the SSTAN FEM-program are provided. All units in the SSTAN output file are in Newtons, millimeters, or combination of these. Positive signs for stress indicates tension, negative signs indicates compression.

Maximum Stresses due to bending

The maximum stress due to bending can be calculated from the bending moments according to equation 5.2:

$$\sigma = (M \times c) / I \qquad \text{(Equation 5.2)}$$

Where:
c = Distance between the neutral axis and top or bottom of the column or beam
I = Moment of Inertia
M = Bending Moment

This gives maximum stresses of 16.4MPa, 45.4MPa, and 13.5MPa for elements 1, 2-3, and 4 respectively. According to the allowable stress design method, the structure will perform adequately when the calculated stresses in the structural members are lower than the allowable stresses. Since the allowable stress was set equal to half of the yield stress of the material, the compressive or tensile yield strengths needed for safe design are 32.8MPA, 90.7MPa, and 27.1MPa for elements 1,2-3,and 4 respectively.

Maximum Normal Stresses at Supports

The maximum normal stresses at nodes 1 and 5 can be calculated by dividing the normal forces at these joints by the columns cross sectional areas. This gives a normal stress of 4.2MPa resulting in maximum allowable stress of 8.4MPa for both supports.

Shear stresses at supports

The maximum shear stresses at supports 1 and 5 can be calculated by dividing the forces in the x direction at these joints by the columns cross sectional areas. This gives

a normal stress of 0.1MPa resulting in maximum allowable shear stresses of 0.2MPa for both supports

Shear stresses at top of columns

Shear stresses at the top of each column can be found accordingly. This results in a shear stress of 1.67MPa and 62.8MPa and a maximum allowable shear stress of 3.34MPa and 125.6MPa for nodes 2 and 4 respectively. The high shear stress at node 4 is due to the difference in deflection of the cables and the frame. It needs to be remembered that a load was placed at node 4 to model the combined action of the wind on leeward and windward walls. In reality, this load is not concentrated at node 4 but distributed equally over all elements. Hence the shear stress obtained at node 4 can be estimated to be similar to the shear stress encountered at node 2.

Shear Stresses at end of Roof Beams

Shear stresses at the end of the beams can also be found accordingly. This results in a shear stress of 1.04MPa and a maximum allowable shear stress of 2.09MPa for both beam-ends.

Displacements

Displacements at nodes 2 and 3 are approximately 63 mm for the X direction. The displacement in the Y direction at the midpoint of the beam is approximately 137 mm. Figure 5.7 provides the deflected shape for the FEM model of the RPC structure, including maximum displacements. A midpoint deflection of 137 mm for a beam spanning 7000mm is approximately equal to a deflection of L/50.

Evaluation and Recommendation

Maximum allowable tensile and compressive yield strengths of about 91 MPa, and a maximum allowable shear strength of 3.4 MPa are needed to make the above design safe (assuming isotropic material properties). These results are higher than the average yield strength of 25 MPa measured for the un-reinforced semi-IPN material (see chapter

4). Therefore, if the design is not to be changed, the material will need to be stronger. This can be accomplished by either increasing the strength of the matrix or by adding high strength fibers to the existing matrix. For example, the addition of 60 percent by volume of continuous E-glass fiber to an epoxy matrix ($\sigma_{tensile} \approx 27$ to 90 MPa) can result in a maximum allowable tensile strength of about 1000 MPa in the direction of the fiber [Callister, 2000]. When fibers in such matrix are randomly and uniformly distributed within one plane, the strength in any direction in this plane should be approximately 3/8 of this value or 375 MPa [Callister, 2000]. However, as pointed out in chapter 4, care must be spent in selecting a proper reinforcement system if such efficiency is to be accomplished. Results provided in chapter 4 for example indicate a tensile strength of only 192 MPa in the direction of the fiber (continuous glass fiber V_f=0.3). When randomly and uniformly distributed discontinuous glass fibers are used, the strength in any direction in this plane should be approximately 3/8 of this value or 72MPa. It is obvious that changing the design could also lower maximum stresses significantly. For example, limiting the span of the roof beam to 3500 mm (by placing a support in middle of the roof) will decrease stress significantly. In this case, the strength of the semi-IPN (25 MPa) without any reinforcement added might suffice (deflection not considered).

The deflection of 137 mm at the midpoint of the 7000 mm long beam is approximately L/50. This relative large deflection is due to the low modulus of elasticity that was used in the analysis (8.5 GPa). The modulus of elasticity of the semi-IPN matrix is approximately 2.5 GPa at 25 °C, being significantly lower then the value used (see chapter 4). Further, most thermosetting matrix systems have a modulus of elasticity very similar to this when tested below the glass transition temperature. Hence, if the design is not to be changed, polymer stiffening is needed. The most efficient way to increase stiffness of polymer systems is to add high strength fibers to them. For example, the

addition of 60 percent by volume of continuous E-glass fiber to an epoxy matrix ($E \approx 2.5$ GPa) can result in a modulus of elasticity of about 45 GPa in the direction of the fiber [Callister, 2000]. When fibers in such matrix are randomly and uniformly distributed within one plane, the stiffness in any direction in this plane should be approximately 3/8 of this value or 16 GPa [Callister, 2000]. As pointed out in chapter 4, care must be spent in designing a proper reinforcement system if such efficiency is to be accomplished. Proper design, such as aligning continuous fibers along the length of the beam, can further result in increased stiffness reducing deflections. In addition, the roof beam could also been given an initial curvature or be pre-stressed to compensate these deflections. As pointed out in the discussion on strength, it is obvious that changing the design could also lower maximum deflection significantly. For example, limiting the span of the roof beam to 3500 mm (by placing a support in middle of the roof) will decrease deflection significantly.

It must be pointed out that the analysis provided above only considered the effects of a limited number of structural loads. In addition, a number of assumptions were made to come to these results. A more complex analysis including for example thermal effects, creep, concentrated loads, and an-isotropic material response are needed before a more conclusive recommendation can be made. A detailed study of structural connections between foundation and the RPC structure is also needed to address such issues as wind uplift and local concentration of stress.

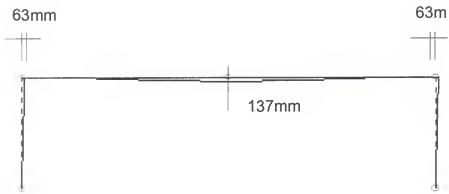


Figure 5.7 Deflected shape of the FEM model for the RPC structure

CHAPTER 6
LIFE CYCLE COST

The implementation of RPC technology in the construction industry needs to be justified economically. To make a correct assessment, the complete life cycle in the application of a particular building design need to be considered. The method most often used to accomplish this objective is called life-cycle-Cost (LCC). LCC can be defined as an economic assessment of an item, area, system, or facility considering all significant costs of ownership over an economic life, expressed in terms of equivalent dollars [Dell 'Isola, 1988]. LCC uses a consistent methodology that enables investors to compare the economical performance of competing systems over a predetermined life cycle. In addition, LCC enables the designer to identify those areas that contribute most to LCC and develop strategies to reduce overall LCC of a building. For economic assessment of a building, significant costs of ownership include initial construction costs, finance costs, operation costs, and maintenance costs. Figure 6.1 provides an overview of all life cycle cost elements relevant to LCC. The objective of this part of the research was to assess the economic performance of rigidified pneumatic composites in the application of a single-family house over an economic life cycle of 40 years. To accomplish this objective, the performance of the new system was compared with the performance of a more conventional system that served as a standard base case.

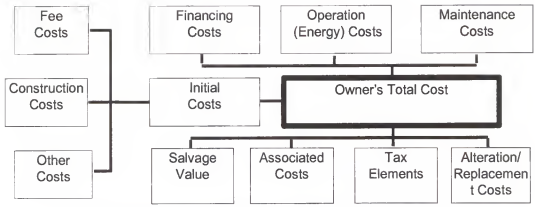


Figure 6.1 Life cycle Cost elements [source: Dell 'Isola, 1988]

Scope and Objectives

The enclosing envelope of a single-family house in its most basic form was considered. This selection was made because one of the main objectives in developing RPC technology is to address the issue of affordable housing. The study focused on the relative differences in performance between the competing systems. The scale of the two houses to be compared was that of a small prismatic single-story house 24 feet wide, 48 feet long, and a ceiling height of 8 feet (about 14mx7mx2.4m). Dimensions and shape are typical for wood light frame (WLF) construction. The building foundation, a frost protected shallow concrete slab, was held constant for both systems. Operation costs for heating and cooling of the building were not considered. These were considered to be identical assuming similar R-values for both systems. Because of this, no operation costs were considered in the LCC calculations. The only variables were materials and methods of construction (exterior walls and roof), and costs for maintenance. Only superstructure and relevant finishing systems are considered. The study did not cover wall openings, mechanical or electrical systems, and issues related to land acquisition. A typical service life of 40 years was selected. Since there exist

significant structural differences between the compared systems, only the primary function of enclosing space was considered. Non-primary functions such as absolute load bearing capacity of each wall assembly are not considered. The present worth method was used for LCC calculations [Dell 'Isola, 1988].

Methods

The present worth method, in which the baseline for comparison is present-day value in equivalent dollar was used for LCC calculations [Dell 'Isola, 1988]. In this method, initial and collateral costs are in present day value and are entered directly. Single future costs (maintenance, replacements) are discounted using present worth factors. Annual costs (operation cost) are entered and multiplied by present worth of annuity factors (PWA-factor). Finally, all present worth amounts were added and used for comparing LCC. Present worth factors and PWA-factors were abstracted from tables provided by Dell' Isola, value engineering in the construction industry [Dell 'Isola, 1988]. Cost elements that were similar for both systems, or were not considered significant were removed from the analysis. All costs were converted to today's dollars by present worth techniques. The financial criteria on which the economic evaluation was based are the following:

Interest Rate	10%
Labor and Material Escalation Rate	0% per annum
Life Cycle Period	40 years

Description Design

Base Case, Wood Light Frame Construction

Figures 6.2 and 6.3 give plan and sections of a typical wood light frame construction placed on a concrete slab on grade.

Wall system

A 2x6 stud wall was selected; studs are placed at a spacing distance of 24 inches on center. A single pressure treated sole plate, and a double top plate is used. Exterior 3/8 inch thick plywood sheeting, exposure 1, is nailed directly to the stud wall providing permanent lateral bracing to the structure and a substrate for placing siding. All wall framing studs are placed in such a way that each stud occurs under each vertical joint between sheeting panels. The exterior sheeting is covered with a polyethylene vapor barrier prior to placing the siding. This layer acts as an air barrier and backup waterproofing layer behind the siding. The siding consists of a PVC exterior cladding system. The interior finish consists of gypsum wallboard nailed to the studs. Two coats of paint are applied to the plaster and serve as the final finishing surface.

Roof and ceiling system

A simple gable roof with a pitch of 5/12 is selected. Rafters and ceiling joists are securely tied together and form a series of triangular W-trusses firmly secured to the top plates of the stud wall. Trusses are also placed at a distance of 24 inches on center. A 1/2 inch thick plywood sheeting is applied to the trusses providing permanent lateral bracing to the roof and a substrate for placing the asphalt shingles. The exterior sheeting is covered with a layer of asphalt saturated felt paper prior to placing the shingles. The shingles are made from die cut heavy sheets of asphalt impregnated felt faced with mineral granules that act as a wearing layer. The roof deck itself is not insulated. The interior finish of the ceiling consists of a 5/8-inch thick gypsum wallboard

panels that are nailed to the ceiling joists. Two coats of paint are applied and serve as the final finishing surface. Roof edges are provided with aluminum drip edges. Table 6.1 provides the inventory of the important components necessary to construct the superstructure of the house.

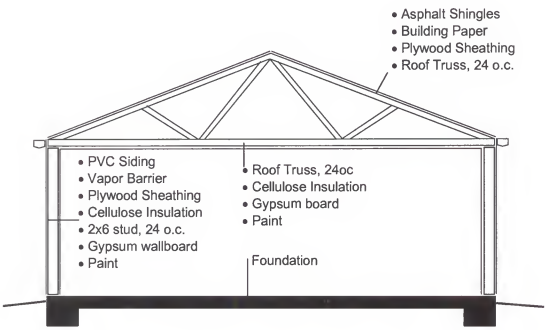


Figure 6.2 Overall Section through WLF structure

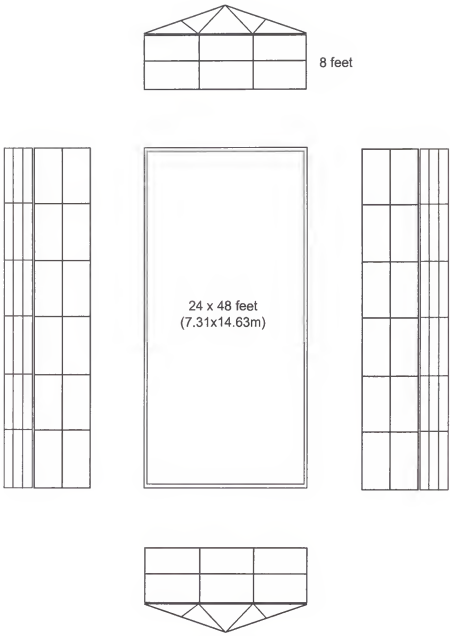


Figure 6.3 Plan, walls, and roof for WLF structure

Table 6.1 Material quantities, Man-hours per unit, and Cost per unit for WLF structure*

Item Description	Quantity	Unit of Measure	Man-hours per Unit	Labor Cost/Unit	Material Cost/Unit	Equipment Cost/Unit	Total Cost/Unit	Total Cost w/OH&P/Unit
WALLS			H/Unit	$/Unit	$/Unit	$/Unit	$/Unit	$/Unit
Rough Carpentry								
Studs 2x6, 24" o.c.	190	m	0.075	1.8	1.44		3.25	4
Sole Plate 2 x 6, 12'	44	m	0.075	1.8	1.44		3.25	4
Double Top Plate 2 x 6	88	m	0.059	1.39	2.24		3.63	4.35
Plywood sheathing 3/8"	107	m2	0.129	3.12	4.74		7.86	9.47
Exterior Finish								
Vapor Barrier, Polyethylene	107	m2	0.032	0.54	0.97		1.51	1.83
Vinyl Siding (0.635mm)	107	m2	0.474	9.9	10.44		20.34	24.97
Interior Finish								
Blown Cellulose, 6"	107	m2	0.118	2.69	4.20	0.97	7.86	9.36
Gypsum board 5/8", taped and spackled	107	m2	0.205	4.31	3.23		7.53	9.47
Plaster, 2 coats	107	m2	0.065	1.18	1.29		2.48	3.01
ROOF								
Rough Carpentry								
"W" Roof trusses, 5 in 12 slope, 24" o.c.	37	Each	1.341	30.65	50.3	10.93	91.88	109
Roof Joists, 2x4	550	m						
Plywood Sheathing on roof, 1/2" thick	112	m2	0.129	3.12	5.81		8.39	10.66
Plywood Sheathing on gable 3/8" thick	10.5	m2	0.129	3.12	4.74		7.86	9.47
Exterior Finish								
Roof deck								
Building Paper	112	m2	0.022	0.43	0.43		0.86	1.08
Asphalt Shingles #240	112	m2	0.139	2.7	3.40		6.1	7.77
Gable								
Vapor Barrier, Polyethylene	10.5	m2	0.032	0.54	0.97		1.51	1.83
Vinyl Siding (0.635mm)	10.5	m2	0.474	9.9	10.44		20.34	24.97
Roof edges								
Aluminum flashing .016"	45	m	0.266	5.85	10.19		16.4	18.96
Vinyl Gutter and down sprouts	29.3	m	0.174	4.11	3.18		7.29	9.09
Interior Finish Ceiling								
Blown Cellulose, 9"	107	m2	0.151	3.44	5.27	0.86	9.58	11.52
Gypsum board on ceiling 5/8", taped and spackled	107	m2	0.237	4.95	6.46		11.41	13.89
Paint (water Based) 2 coats	107	m2	0.097	1.94	1.18		3.12	3.88

*Unit cost data was obtained from the Dodge Metric Unit Cost Book, 1997 edition

RPC Construction

Figure 6.4 and 6.5 give plan and sections of an RPC construction placed on a concrete slab on grade.

Wall System

A 0.2 m thick wall composed of tubular rectangular column elements 0.2 m wide and 0.2 m deep is envisioned. A single-ply butyl-rubber membrane covers the exterior surface of the wall structure and provides protection against environmental elements (rain, UV-light, puncture). No interior finishes are included, the membrane will provide these functions. A membrane thickness of 0.4 mm was selected according to the structural analysis provided in chapter 5.

Roof and Ceiling System

No effort was made to resemble the shape of a gable roof. The roof structure consists of tubular rectangular beam elements 0.2 m wide and 0.4 m high. The top of the beams is slightly curved to allow for rainwater to run down. The interior ceiling height is 8 feet. A single-ply butyl-rubber membrane covers the exterior surface of the roof structure and provides protection against environmental elements. No interior finishes are included, the membrane will provide this function. A membrane thickness of 0.4 mm was adopted according to the results obtained from the structural analysis provided in chapter 5. Table 6.2 provides the inventory of the major components necessary to construct the superstructure of the RPC house.

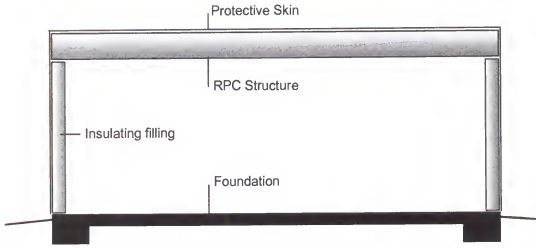


Figure 6.4 Overall Section through RPC structure

Table 6.2 Material quantities used in RPC construction

Item Description	Quantity	Unit of Measure	Man-hours per Unit	Labor Cost/Unit	Material Cost/Unit	Equipment Cost/Unit	Total Cost/Unit	Total Cost w/OH&P/Unit
WALLS								
RPC Structure	175	Kg	x	x	x	x	x	14.26
Blown Cellulose*, 9"	106	m2	0.151	3.44	5.27	0.86	9.58	11.52
Protective Skin, Butyl* 1/16"	125	m2	0.215	4.09	6.46		10.55	12.59
ROOF								
RPC Structure	200	Kg	x	x	x	x	x	14.26
Blown Cellulose*, 9"	106	m2	0.151	3.44	5.27	0.86	9.58	11.52
Protective Skin, Butyl* 1/16"	125	m2	0.215	4.09	6.46		10.55	12.59

*Unit cost data was obtained from the Dodge Metric Unit Cost Book, 1997 edition

Figure 6.5 Plan, walls, and roof for RPC construction

Cost Components

Wood Light Frame Structure

Construction cost

Construction cost data for the wood light frame construction was obtained separately for a) materials, b) labor, c) equipment, d) total Cost (a+b+c), and e) total cost including overhead and profit. Construction cost data and construction time was estimated using data obtained from the Dodge Metric Unit Cost Book (1997). The quantities provided in Table 6.1 were used for this cost estimate.

Maintenance cost

Maintenance needs for the wood light frame structure involves repair of exterior and interior surfaces at different points in time. One major renovation was calculated for after 20 years of service (half of the useful life). For the exterior walls this was estimated to include replacing 50 % of all the vinyl siding. The replacement frequency for aluminum siding was taken (35 years, 100 % replaced) and modified to 50% replacement after 20 years. Maintenance costs for the roof was estimated to involve replacing of all roofing shingles after 20 years. No maintenance costs for interior walls and ceiling was included, the assumption was made that these operations would be similar in cost for both systems. Maintenance costs were considered as single expenditures at these different time intervals. Figure 6.6 illustrates time intervals for each maintenance operation over the complete 40 year service life. Cost data was obtained from the Dodge Metric Unit Cost Book (1997). Maintenance and repair intervals for these activities were obtained from the RS-MEANS, Facilities maintenance and repair cost data (1994).

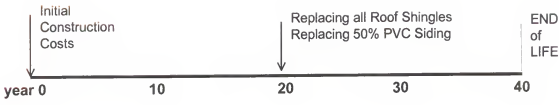


Figure 6.6 Construction & maintenance costs WLF structure over 40 years

RPC Structure

Construction cost

Since no historic construction cost data is available for RPC structures, surrogate data needed to be found. Cost was obtained by means of a survey of retail prices of mass produced plasticized PVC items such as inflatable air mattresses and swimming pools. The weight of several items was obtained and divided by its retail price. From this an average cost per weight could be established. After this, the cost for raw materials (PVC+plasticizer) was obtained. From these two (raw material cost and retail price), a factor for profit could be determined. The next step involved calculating the raw material cost for materials used in the actual RPC membrane and multiplying this with this profit factor. This cost per weight could then be used to calculate the total cost of the RPC membrane (site delivery and inflation not included). Figure 6.7 provides an overview of this method. This method assumed that the RPC structure was a mass-produced item delivered on site ready for inflation. It was also assumed that the cost of a material with sufficient strength would not differ significantly from the cost of the material tested in chapter 4. The total construction time needed to erect the RPC structure was estimated as 64 man-hours, or 4 days for a crew of two people.

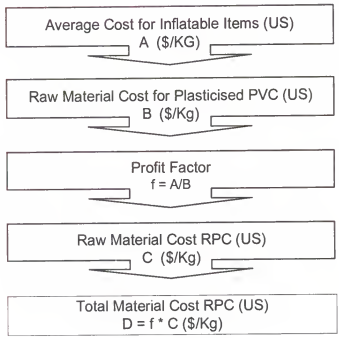

Average Cost for Inflatable Items (US)
A ($/KG)
Raw Material Cost for Plasticised PVC (US)
B ($/Kg)
Profit Factor
f = A/B
Raw Material Cost RPC (US)
C ($/Kg)
Total Material Cost RPC (US)
D = f * C ($/Kg)

Figure 6.7 Method for Calculating Cost RPC Structure

Maintenance cost

Maintenance needs for RPC structures will be different than for more conventional construction systems. Walls and roof are composed of thin membranes that are inflated and rigidified. In a second phase, an insulation system is put in place. Since membranes are structural, any damage to them can possibly compromise structural integrity. For this reason, a skin made from butyl rubber was provided to protect the exterior surface of the structure. For maintenance, this protective envelope will need to be replaced after 20 years of service (half the service life). No maintenance costs for interior walls and ceiling was included, the assumption was made that these operations would be similar in cost for both systems. Maintenance costs were considered as single expenditures at

these different time intervals. Cost data was obtained from the Dodge Metric Unit Cost Book (1997). Maintenance and repair intervals for these activities were obtained from the RS-MEANS, Facilities maintenance and repair cost data (1994). Figure 6.9 illustrates time intervals for each maintenance operation over the complete 40 year service life.

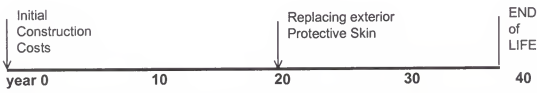


Figure 6.8 Construction & maintenance costs RPC structure over 40 years

Cost Factors held Constant for Wood Light Frame and RPC Structure

Operation cost

Operating cost is a significant cost factor if calculated over the complete service life of a house. Many factors effect energy expenditures, including thermal properties of materials, air infiltration rate, exposed surface area, design configuration, and climate conditions. No differences in design configuration, air infiltration rate, climate conditions, or overall thermal performance of foundation, walls, or roof were considered between the wood light frame and the RPC structure. Hence, the energy demand and operation costs for HVAC was assumed to be identical for both systems.

Financing cost

An interest rate of 10% was used for financing both systems

Other costs

No salvage value, associated costs, tax elements, alteration costs, real estate cost, or design costs were included in this study.

Cost Component Results

Wood Light Frame Construction

Construction cost

The estimated construction cost for the wood light frame construction is provided in table 6.4. The tables provide a cost break down for materials, labor, equipment, total cost, and total cost including overhead and profit. The time needed to perform each task is also provided. The total construction cost to erect the wood light frame structure was estimated to be $17081, not including the foundation system.

Maintenance cost

The maintenance costs for the wood light frame construction is provided in table 6.3. The table provide a cost break down for materials, labor, equipment, total cost, and total cost including overhead and profit. The time needed to perform each task is also provided. The renovation cost for the wood light frame structure was estimated to be $3230 for the exterior surfaces (after 20 years) and $737 for the interior surfaces (every 10 years).

RPC Structure

Construction cost

Table 6.5 provides the cost per kilogram for some mass produced inflatable items, also including an average cost per kilogram. Table 6.6 provides the raw material cost for simple plasticized PVC including a fabric Table 6.7 provides the estimated raw material

cost for the RPC membrane. Table 6.8 provides specific gravity for the RPC membrane. Finally, table 6.9 provides estimated construction cost for the RPC structure. Cost for walls and roof are provided separately.

Maintenance cost, RPC structure

The estimated maintenance costs for the RPC structure is provided in table 6.10. The table provide a cost break down for materials, labor, equipment, total cost, and total cost including overhead and profit. The time needed to perform each task is also provided. The renovation cost for the RPC structure was estimated to be $3148 for the exterior surfaces (after 20 years).

Table 6.3 Estimated renovation costs Wood Light Frame Structure (after 20 years)

Item Description	Original Quantity	% replaced after 20 years	Quantity	Unit of Measure	Man-hours (Hrs)	Labor Cost ($)	Material Cost ($)	Equipment Cost ($)	Total Cost ($)	Total Cost w/OH&P ($)
WALLS										
Exterior Finish			0							
Vapor Barrier, Polyethylene	107	50	53.5	m2	1.71	28.9	52	0	81	98
Vinyl Siding (0.635mm)**	107	50	53.5	m2	25.4	530	559	0	1088	1336
ROOF			0							
Exterior Finish			0							
Roof deck			0							
Install new shingles over existing*	112	100	112	m2	32	732	516	0	1687	1988
Gable			0							
Vapor Barrier, Polyethylene	10.5	50	5.25	m2	0.17	2.84	5	0	8	10
Vinyl Siding (0.635mm)**	10.5	50	5.25	m2	2.49	52	55	0	107	131
TOTALS					**62**	**1346**	**1187**	**0**	**2970**	**3562**

* Cost data was obtained from MEANS, Facilities maintenance and repair cost data (94)

** The replacement frequency for aluminum siding was taken (35 years, 100 % replaced) and modified to 50% replacement after 20 years.

Table 6.4 Summary of estimated construction costs Wood Light Frame Structure

Item Description	Quantity	Unit of Measure	Manhours (Hrs)	Labor Cost ($)	Material Cost ($)	Equipment Cost ($)	Total Cost ($)	Total Cost w/OH&P ($)
WALLS								
Rough Carpentry								
Studs 2x6, 24" o.c.	190	m	14.25	342	274	0	618	760
Sole Plate 2 x 6, 12'	44	m	3.3	79.2	63	0	143	176
Double Top Plate 2 x 6	88	m	5.192	122.3	197	0	319	383
Plywood sheathing 3/8"	107	m2	13.8	333.8	507	0	841	1013
Exterior Finish			0	0	0	0	0	0
Vapor Barrier, Polyethylene	107	m2	3.424	57.78	104	0	162	196
Vinyl Siding (0.635mm)	107	m2	50.72	1059	1117	0	2176	2672
Interior Finish			0	0	0	0	0	0
Blown Cellulose, 6"	107	m2	12.63	287.8	449	104	841	1002
Gypsum board 5/8", taped and spackled	107	m2	21.94	461.2	346	0	806	1013
Plaster, 2 coats	107	m2	6.955	126.3	138	0	265	322
ROOF			0	0	0	0	0	0
Rough Carpentry			0	0	0	0	0	0
"W" Roof trusses, 5 in12 slope, 24" o.c.	25	Each	33.53	766.3	1258	273	2297	2725
Roof Joists, 2x4	550	m	0	0	0	0	0	0
Plywood Sheathing on roof, ½" thick	112	m2	14.45	349.4	651	0	940	1194
Plywood Sheathing on gable 3/8" thick	10.5	m2	1.355	32.76	50	0	83	99
Exterior Finish			0	0	0	0	0	0
Roof deck			0	0	0	0	0	0
Building Paper	112	m2	2.464	48.16	48	0	96	121
Asphalt Shingles #240	112	m2	15.57	302.4	381	0	683	870
Gable			0	0	0	0	0	0
Vapor Barrier, Polyethylene	10.5	m2	0.336	5.67	10	0	16	19
Vinyl Siding (0.635mm)	10.5	m2	4.977	104	110	0	214	262
Roof edges			0	0	0	0	0	0
Aluminum flashing .016"	45	m	11.97	263.3	459	0	738	853
Vinyl Gutter and down sprouts	29.3	m	5.098	120.4	93	0	214	266
Interior Finish Ceiling			0	0	0	0	0	0
Blown Cellulose, 9"	107	m2	16.16	368.1	564	92	1025	1233
Gypsum board on ceiling 5/8", taped and spackled	107	m2	25.36	529.7	691	0	1221	1486
Paint (water Based) 2 coats	107	m2	10.38	207.6	126	0	334	415
TOTALS			**274**	**5967**	**7635**	**469**	**14031**	**17081**

Table 6.5 Estimated average cost per kilogram for mass-produced inflatable items

	Item description	Item Weight (lb)	Item Weight (Kg)	Item Retail Price ($)	Price/Kg ($/Kg)
	Various*				
1	Air mattress		1.318	7.99	6.1
2	Air mattress		1.614	6.89	4.3
3	Air mattress		3.5	17.99	5.1
4	Air mattress		0.716	3.99	5.6
5	Pool tire		0.35	2.99	8.5
6	3 Ring Pool		1.8	14.99	8.3
7	Rect. Pool		17	89.99	5.3
8	3 Ring Pool		1.05	7.99	7.6
9	Ring		5	49.99	10.0
10	Capsule		10	99.99	10.0
11	Air mattress +...		5	29.99	6.0
12	Big Rectangular Pool		9.5	179.99	18.9
13	Pool Toy/Floater		1.182	14.99	12.7
	Air Mattresses**				
14	PVC	11	4.99	89.99	18.04
15	PVC	12	5.44	119.99	22.04
16	PVC	13	5.90	139.99	23.74
17	PVC/ Nylon	8.6	3.90	34.99	8.97
18	PVC/Nylon	12	5.44	44.99	8.27
19	PVC/Nylon	15	6.80	49.99	7.35
20	PVC/Nylon	11	4.99	99.99	20.04
21	PVC/fabric top	6.4	2.90	24.99	8.61
22	PVC/fabric top	8.4	3.81	34.99	9.18
23	PVC/fabric top	11	4.99	44.99	9.02
24	Nylon over PVC	6.4	2.90	34.99	12.05
25	Nylon over PVC	8	3.63	49.99	13.78
26	Nylon over PVC	9.4	4.26	54.99	12.90
27	Nylon over PVC	12	5.44	74.99	13.78
28	Velour over PVC	6.2	2.81	29.99	10.66
29	Velour over PVC	7.9	3.58	34.99	9.76
30	Velour over PVC	9.3	4.22	39.99	9.48
31	PVC	5.7	2.59	19.99	7.73
32	PVC	7.7	3.49	24.99	7.16
33	Rayon over PVC	5.2	2.36	19.99	8.48
34	Rayon over PVC	7	3.18	24.99	7.87
A	**Average cost per Kg finished product**				**10.51**
B	**Cost raw materials (see table 6.6)**				**3.05**
F	**Profit Factor**				**3.45**

* Retail prices and item weights were obtained from Target retail stores (1999)

** Retail prices and item weights were obtained from the 1999 JC Penny catalogue

Table 6.6 Estimated raw material cost for simple plasticized PVC + fabric

Product	Product name	Reference	$/Kg	Parts by Weight	Weight %	$/Kg Matrix
PVC	GEON 129	GEON	1.10	100	0.284	0.313
Plasticizer	DOP	Eastman	1.41	50	0.142	0.200
Epoxidized Soybean Oil	Flexol EPO	Union Carbide	2.14	10	0.028	0.061
CaZn PVC stabilizer	Thermcheck	Ferro	9.59	2	0.006	0.054
Filler	CaCO3	Union Carbide	0.11	20	0.057	0.006
Cotton Fabric			5	170	0.48	2.415
Total						**3.050**

Table 6.7 Estimated raw material cost RPC membrane

Product	Product	Reference	Purchase Quantity	$/1 Kg	Parts by Weight	Weight %	$/Kg
PVC	GEON 129	GEON	Truckload	1.37	100	0.279	0.381
Reactive Plasticizer	SB520A210	Sartomer	44 drums	6.64	70	0.195	1.294
Epoxidized Linseed Oil	Flexol LOE	Union Carbide	65 drums	2.67	15	0.042	0.111
Photo-initiator	Irgacur 369	Ciba	440 lb	93.63	2	0.006	0.522
CaZn PVC stabilizer	Thermcheck	Ferro	1 Drum	9.59	2	0.006	0.053
E-Glass Reinforcement		Callister, 2000		3.75	170	0.474	1.776
Total Cost/ Kg					359	1.000	**4.137**
Profit factor							3.45
Total Cost / Kg							**14.26**

Table 6.8 Specific gravity composite

Product	PBW	Weight fraction	Specific Gravity	Volume fraction	Weight fraction/ L
			Kg/Liter		Kg/Liter
PVC	100	0.279	1.4	0.32	0.453
Reactive Plasticizer	70	0.195	1.080	0.29	0.317
Epoxidized Linseed Oil	15	0.042	1.030	0.07	0.0680
Photo-initiator	2	0.006	1.000	0.01	0.009
CaZn PVC stabilizer	2	0.006	1.100	0.01	0.009
E-Glass Reinforcement	170	0.474	2.58	0.30	0.7709
Specific gravity composite					**1.6279**

Table 6.9 Estimated construction costs RPC Structure

Item Description	Quantity	Unit of Measure	Man-hours	Labor Cost	Material Cost	Equipment Cost	Total Cost	Total Cost w/OH&P
WALLS								
Membrane	175	Kg	8					2496
Blown Cellulose, 9"	106	m2	16	364.6	559	91	1015	1221
Protective Envelope, Butyl 1/16"	125	m2	8	511.3	808	0	1319	1574
ROOF								
Membrane	200	Kg	8					2852
Blown Cellulose, 9"	106	m2	16	364.6	559	91	1015	1221
Protective Envelope, Butyl 1/16"	125	m2	8	511.3	808	0	1319	1574
TOTALS			**64**					**10937**

Table 6.10 Estimated cost for replacing protective envelope (after 20 years).

Item Description	Quantity	Unit of Measure	Man-hours	Labor Cost	Material Cost	Equipment Cost	Total Cost	Total Cost w/OH&P
WALLS								
Protective Envelope, Butyl 1/16"	125	m2	26.88	511.3	808	0	1319	1574
ROOF								
Protective Envelope, Butyl 1/16"	125	m2	26.88	511.3	808	0	1319	1574
TOTALS			**54**	**511**	**808**	**0**	**1319**	**3148**

LCC Calculations

Cost of Ownership calculation, Wood Light Frame Structure

1) Present worth of initial cost equals the estimated initial cost of the structure. Initial cost = $17081.

2) Present worth of the interest costs equals the present worth of the annual difference of payoff with interest less the payoff without interest [Dell 'Isola, 1988]. Annual charge with interest equals initial costs times periodic payment necessary to pay off a loan of $1 = 17081 * 0.102259 = 1747. Annual charge without interest equals initial costs divided by number of years = 17081/40=$/year 427. The difference = $/year1320, which is the annual value of interest. The present worth of interest = $1320 * 9.77 = $12896

3) The present worth of the major renovation costs (after 20 years) = cost in future years times present worth of $1 due in the future = $3562 *0.148 = $530 (0% escalation).

Figure 6.10 presents the Cash Flow Diagram for the wood light frame structure over a service life of 40 years.

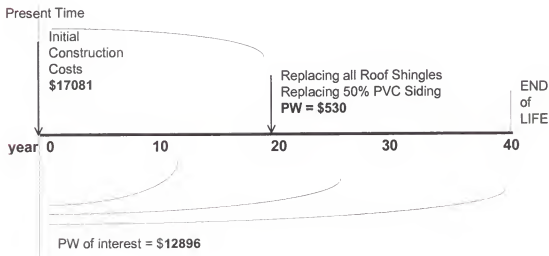


Figure 6.9 Cash flow diagram wood light frame structure (40 years)

Cost of Ownership calculation, RPC Structure

1) Present worth of initial cost equals the estimated initial cost of the structure. Initial cost = $10937

2) Present worth of the interest costs equals the present worth of the annual difference of payoff with interest less the payoff without interest [Dell 'Isola, 1988]. Annual charge with interest equals initial costs times periodic payment necessary to pay off a loan of $1 = 10937 * 0.102259 = 1118. Annual charge without interest equals initial costs divided by number of years = 10937/40 = $/year 273. The difference = $/year 845, which is the annual value of interest. The present worth of interest = $845 * 9.77 = $8255

3) The present worth of the major renovation costs (after 20 years)= cost in future years times present worth of $1 due in the future = $3148 * 0.148 = $466 (0% escalation).

Figure 6.10 presents the Cash Flow Diagram for the wood light frame structure over a service life of 40 years.

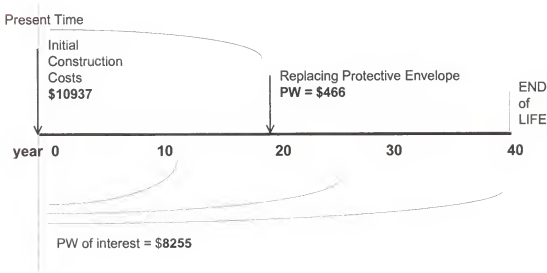


Figure 6.10 Cash flow diagram wood light frame structure (40 years)

Results and Discussion

Results

According to the above calculations, the cost of ownership in present day values are $30507 and $19658 for the wood light frame and RPC structure respectively (not including foundation and operation costs). Hence, the RPC structure is approximately 35% less expensive than the WLF structure. The net savings in present day value is $10849 for this particular design. Figure 6.11 represents the cost breakdown for both systems. Approximately 56 % of the costs are due to initial construction, 42 % is due to interest, the rest accounts for the major renovation of both proposals after 20 years. Finally the estimated time for construction for the WLF structure is 296 man-hours compared to 64 man-hours for the RPC structure.

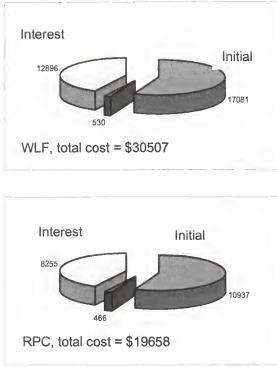


Figure 6.11 Cost breakdown for WLF and RPC structures.

Discussion

An approximate difference of 35% in cost of ownership is fairly significant. However considering the high risks involved with the implementation of this new construction technology, this difference may not be enough yet. In addition, a total initial cost of about $10937 is still beyond the reach of many individuals or families living in less developed countries. The cost of the RPC structure is a result of the cost of initial construction and the resulting interests that need to be paid. Figure 6.12 provides a cost breakdown for the initial construction cost of the RPC structure.

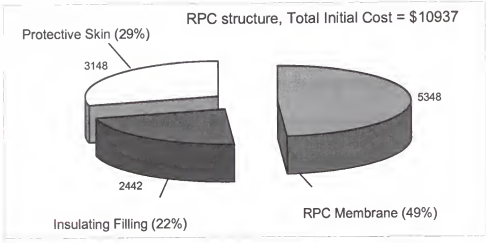


Figure 6.12 Cost breakdown initial construction cost of the RPC structure ($)

A number of assumptions were made to come to these results. First, the cost of the RPC membrane was calculated by multiplying the cost of the raw materials with a profit factor. This profit factor embodied an averaged profit made upon retail of mass produced inflatable items sold in the US. When comparing this profit factor with the profit made in the construction of the wood light frame structure, significant differences exist.

The wood light frame structure, for which the material cost is approximately $7635 and the final cost (including overhead and profit) is $17081, applies a profit factor of 2.24. The profit factor used for the wood light frame structure is thus significantly lower than the one used to calculate the cost of the RPC structure (3.45). The use of a lower profit factor to calculate initial construction of the RPC structure may thus be appropriate. Applying the lower profit factor of 2.24 to the RPC membrane structures gives a total initial construction cost of $9055. Both the cost of the protective skin and the insulating filling remain unaffected as illustrated in figure 6.13. Considering the high degree of automation according to which RPC structures can be pre-manufactured (relative to the labour intensive methods used in more regular construction technologies), an even lower profit factor can be defended. The profit factor of 3.45 can be regarded as an approximate upper limit for profit for this kind of construction, with the lowest factor for profit being 1 (no profit).

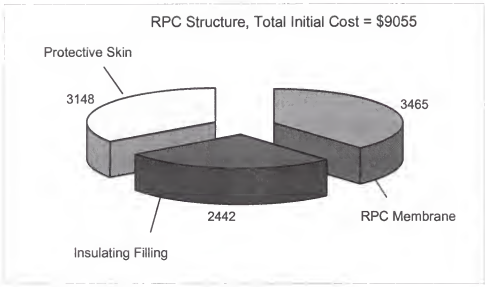


Figure 6.13 Cost breakdown for the initial construction cost of the RPC structure using a profit factor of 2.24 instead of 3.45 ($).

In addition to the cost of the structural RPC membrane, both the protective skin and the insulating filling make up a substantial portion of the total initial construction cost of the proposed design (51%). The identification of lower cost fillings, such as foam-plastic waste used in packing, could reduce this cost. If insulation is not critically important, no filling, or a lower cost filling such as sand (walls) can further eliminate or reduce the cost of this filling. Similar thoughts apply to the external protective skin, which makes up a substantial portion of the total construction cost. The main purpose of this skin is to protect the structural RPC membrane from environmental degradation. The identification of lower cost skins or other means of protecting the membrane may eliminate or reduce this cost. If no external skin or expensive filling were used for the above design, the initial construction cost would be approximately $3465 (profit factor of 2.24). Development of lower cost RPC materials and materials having higher strength and stiffness can further reduce cost significantly. Finally, more appropriate design might also cut initial construction cost. For example, replacing the roof structure with a tensile membrane supported by the external walls could proof beneficial. In such proposal, only the external walls needs to resist compressive and bending stress. Since the roof is in tension, much less material can be used for this part of the building.

CHAPTER 7
ENVIRONMENTAL CONSIDERATIONS

Concern for global environment requires the assessment of environmental impacts of new and existing technologies. Similar to LCC, a correct assessment can only be made if the complete life cycle is considered. The method most often used to accomplish this objective is called life-cycle-Assessment (LCA). The essence of LCA is the examination, identification, and evaluation of the relevant environmental implications of a material, process, product, or system across its life span [Graedel, 1998]. LCA uses a consistent methodology that enables designers to compare the environmental performance of competing systems over a predetermined life cycle. In addition, LCA enables the designer to identify those areas of a project that cause the most burden to the environment. From this, strategies can be developed to reduce overall impact. When assessing the environmental performance of for example a building, it is recommended to perform an input-output analysis for each of the different life cycle stages. Such assessment starts with identifying the various life cycle stages of the building. After these have been established, an inventory is prepared that describes all the material and energy inputs and waste outputs for each of these life cycle stages (figure 7.1). Once these have been quantified, performance of competing systems can be compared and evaluated. A priority listing of environmental performance criteria is used in this final evaluation. While a complete life cycle assessment provides the most objective information for further decision-making, in reality such assessments are never done. Main reasons for this are: 1) insufficient data available to quantify inputs and

outputs at various life cycle stages, 2) Inconsistency in data due to the large variety of for example industrial practices to produce a single product, 3) Time involved to perform such studies. Because of these difficulties, it becomes more common to perform a life cycle assessment for which overall scope has been limited. The philosophy for such streamlined approach is to limit the amount of information (to make the study practical) without decreasing confidence in the outcome. Means available to limit scope are for example: 1) include only those life cycle stages assumed to significantly effect the outcome of the study, 2) only include those items present above a certain threshold value, 3) use lists of established environmental mal-practices to identify areas that need special attention. Life cycle screening is perhaps the most efficient tool to assess or identify those areas that require special attention. In this screening, the various life cycle stages are not necessarily considered separately but can be lumped together for the entire process, product, or service. This allows for fast evaluation and identification of areas that require special attention. Figure 7.2 illustrates the spectrum of available environmental assessment tools. The objective of this part of the research was to provide such an initial environmental screening for RPC technologies.

Scope and Objectives

It is widely agreed that systems that use comparable materials for construction will perform better environmentally when less quantities of these materials are used. This less is better approach is justified by the fact that less resources are used; hence the negative impacts of resource consumption will also decrease [Graedel, 1998]. The objective of this part of the research was to perform such an initial environmental screening. In this, the environmental performance of RPC structures was evaluated in the application of a single-family house. To accomplish this objective, the performance of the new system was compared with the performance of a more conventional system

(WLF) that served as a standard base case. The approach is therefore similar to the approach used to determine LCC. The study will compare the amount and type of materials used to build a single-family house using the case studies of previous chapter. The study focused on the relative differences in performance between the competing systems. The building foundation, a frost protected shallow concrete slab, was held constant for both systems and was not included in the evaluation. Operation costs for heating and cooling of the building were not considered. These were considered to be identical assuming similar R-values for both systems. The only variables were materials and methods of construction (exterior walls and roof). Only superstructure and relevant finishing systems are considered. The study did not cover wall openings, mechanical or electrical systems.

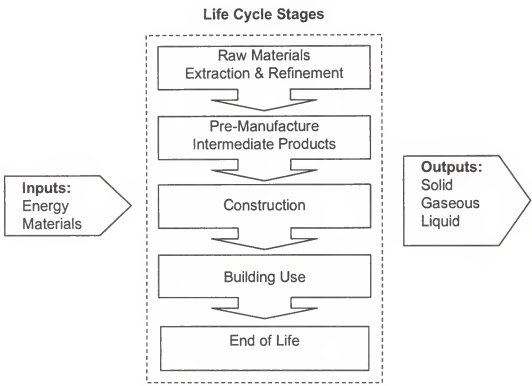


Figure 7.1 Input-output analyses at various life cycle stages

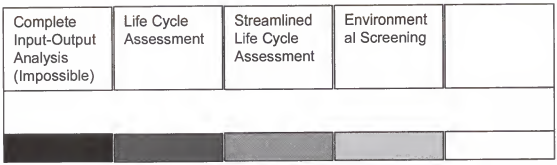


Figure 7.2 Spectrum of some environmental assessment tools

Methods

First, the quantities used to estimate the initial construction cost of both RPC and wood light frame construction (previous chapter) were translated into a common denominator (volume and weight). Second, materials for each system were classified into categories of materials having similar origin or nature. Categories used were: a) materials coming from wood, b) materials coming from fossil resources, and c) materials coming from inorganic matter. Materials present in small quantities were not included. Finally, these results were used to assess the environmental performance of RPC structures relative to the wood light frame construction system. From this, recommendations could be made.

Results

Amount of Materials

The estimated weight and volume of the different materials needed to construct the WLF structure and RPC structure are provided in table 7.1.and 7.2 respectively. Estimated total volumes of 52 m^3 and 49 m^3 are needed to erect the wood light frame

system and the RPC structure respectively. This resulted in total construction masses of 10424 Kg and 3248 Kg for the WLF system and the RPC structure respectively.

Amount of Materials per Category

Tables 7.1 and 7.2 also provide the amount of materials per category for the two systems, table 7.3 further summarizes these results. The amount of materials coming from wood is 5794 Kg and 2423 Kg for the WLF and RPC structures respectively. The amount of materials coming from fossil resources is 1220 Kg and 630 Kg for the WLF and RPC structures respectively. The amount of materials coming from inorganic matter is 3397 Kg and 180 Kg for the WLF and RPC structures respectively.

Discussion

The above results are significant in several ways. First, a typical WLF uses significant amounts of products coming from fossil remains (petroleum, coal, natural gas). These include for example: the glues that hold the exterior plywood together (178 Kg), the polyethylene vapor barrier (11 Kg), the Poly-Vinyl-Chloride siding (104 Kg), the interior paints (22 Kg), and the asphalt shingles on the roof (896 Kg). Combined, these make up 12% of the weight of the structure. Second, a significant portion of the mass for WLF comes from inorganic matter (3397 Kg). These are the gypsum boards used to finish interior walls and ceiling. Combined this make up 33 % of the structure. Finally, 55% of the weight of the WLF structure comes from wood, being the structural framework. These include the 2x6 studs of the wall (1371 Kg), the wood used in the W-shaped roof trusses (781 Kg), the wood present in the plywood sheathing (1601Kg), and the cellulose insulation (2038 Kg). The results for the RPC structure are quite different from these. First, the RPC structure is extremely lightweight (3248 Kg) compared to the wood light frame structure (11943 Kg). Second, only 630 Kg or 19 % of the total weight comes from fossil resources, this incorporates the polymeric matrix used in the

membrane and the rubber used as protective skin. The WLF structure in contrast uses a total of 2249Kg of products derived from petroleum. Third, the amount of inorganic matter present in the RPC structure is 180 Kg or 6% of the total weight. This represents the glass-fiber reinforcement present in the membrane. Finally, about 75 % of the weight of the RPC structure comes from wood (2423 Kg). This is the cellulose insulation system inserted in the cavities of the RPC structure. Figure 7.1 compares these results for each category used in both systems. Figures 7.3 and 7.4 give the weight % of each category of materials used in both systems.

These results indicate that the use of RPC composite materials can provide significant environmental benefits. First, since comparable resources are used in lesser amounts (relative to the WLF structure), the environmental impacts of resource consumption will also be less. Second, no wood is used as structural material in the RPC system, hence no trees need to be cut for this purpose. This could have significant environmental benefits since more land could become available for natural forests. Third, the use of fewer resources will also ease the waste management problem afterwards. In addition to this, RPC structures are also more homogeneous in composition facilitating the separation of wastes resulting in more convenient recycling of the materials. Finally, the RPC structure provides significant weight savings resulting in less energy use during transportation.

It is clear however that the above results could be quite different when different system components were selected. This is true for both the WLF and RPC structures. For example, substituting the PVC siding with wood siding reduces the use of fossil resources to 10% of the total weight of the wood light frame structure and increases the use of wood to 60% of the total weight. Figure 7.2 compares the results for the WLF structure using a 10mm thick wood siding relative to the RPC structure (for each

category). Even in this case, the WLF structure uses almost twice the amount of resources coming from fossil remains relative to the RPC structure. Replacing the asphalt shingles with another roof material can further reduce the use of products derived from fossil resources. Similar substitutions can be done for the RPC structures. For example, replacing the poly vinyl chloride of the semi-IPN matrix system with a cellulose based polymer (coming from wood or other plants), and replacing the acrylate based reactive plasticizer with one derived from natural oils (such as soybean or linseed oil) can result in a product in which no petroleum derived polymers are used. Also, when replacing the glass reinforcement with a natural reinforcing fiber (such as cotton, flax, or hemp) an RPC membrane can be composed of materials that are completely derived from renewable resources. Additional research is needed to assess the environmental performance of such systems.

Table 7.1 Estimated amounts of materials and amount per category for wood light frame structure

Item Description	Volume (m3)	Specific Gravity (kg/m3)***	Mass (Kg)	Category*	From wood (Kg)	Fossil (Kg)	Inorganic matter (Kg)
WALLS							
Rough Carpentry							
Studs 2x6, 24" o.c.	1.47	550	809	W	809		
Sole Plate 2 x 6, 12'	0.34	550	187	W	187		
Double Top Plate 2 x 6	0.68	550	375	W	375		
Plywood sheathing 3/8" **	1.02	700	713	.9W+.1P	642	71	
Exterior Finish			0				
Vapor Barrier, Polyethylene	0.01	920	10	P		10	
Vinyl Siding (0.635mm)	0.07	1400	95	P		95	
Interior Finish			0				
Blown Cellulose, 6"	16.31	50	815	W	815		
Gypsum board 5/8", taped and spackled	1.70	1000	1699	I			1699
Paint, 2 coats	0.01	1000	11	P		11	
ROOF	0.00		0				
Rough Carpentry	0.00		0				
"W"- Roof trusses, 5 in 12 slope.			0				
Roof Joists, 2x4	1.42	550	781	W	781		
Plywood Sheathing on roof, 1/2" thick**	1.42	700	996	.9W+.1P	896	100	
Plywood Sheathing on gable 3/8" thick**	0.10	700	70	.9W+.1P	63	7	
Exterior Finish			0				
Roof deck			0				
Building Paper	0.01	550	3	W	3		
Asphalt Shingles #240	0.90	1000	896	P		896	
Gable	0.00		0				
Vapor Barrier, Polyethylene	0.00	920	1	P		1	
Vinyl Siding (0.635mm)	0.007	1400	9	P		9	
Roof edges	0.00		0				
Aluminum flashing	0.00	2700	12	M			
Vinyl Gutter and down sprouts	0.01	1400	10	P		10	
Interior Finish Ceiling	0.00		0				
Blown Cellulose, 9"	24.46	50	1223	W	1223		
Gypsum board on ceiling 5/8", taped and spackled	1.70	1000	1699	I			1699
Paint, 2 coats	0.01	1000	11	P		11	
TOTALS	**51.64**		**10424**		**5794**	**1220**	**3397**

* W = Wood, P = Petroleum, I = Inorganic, M = Metal

** W/P = 90% Wood/ 10% polymer [Seller, 1985]

*** Specific gravities were obtained from Callister, 2000

Table 7.2 Estimated amounts of material and amounts per category for RPC structure

Item Description	Volume (m3)	Specific Gravity (kg/m3)***	Mass (Kg)	Category*	From wood (Kg)	Fossil (Kg)	Inorganic matter (Kg)
WALLS							
Membrane **	0.15	**1161**	175	**P/I**		**84**	**84**
Blown Cellulose, 9"	24.23	50	1212	W	1212		
Protective Envelope, Butyl 1/16"	0.19	1200	225	P		225	
ROOF			0				
Membrane **	0.17	**1161**	200	**P/I**		**96**	**96**
Blown Cellulose, 9"	24.23	50	1212	W	1212		
Protective Envelope, Butyl 1/16"	0.19	1200	225	P		225	
TOTALS	**49**		**3248**		**2423**	**630**	**180**

* W = Wood, P = Petroleum, I = Inorganic

** P/I = 50% Inorganic / 50% Petroleum

*** Specific gravities were obtained from Callister, 2000

Table 7.3 Summary results of estimated amounts of material and amounts per category for wood light frame structure and RPC structure

	m3	Kg	From wood	Fossil	Inorganic matter
Wood Light Frame	51.64	10424	5794	1220	3397
RPC	49	3248	2423	630	180

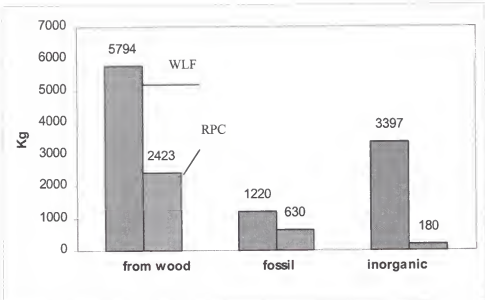


Figure 7.1 Composition in Kg for each category for WLF (using PVC siding) and RPC structures

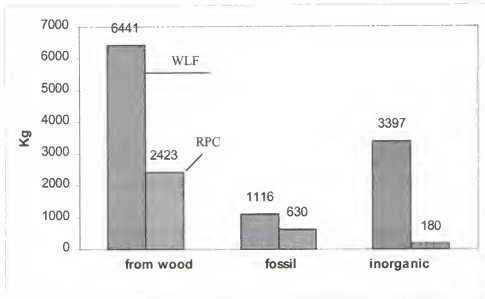


Figure 7.2 Composition in Kg for each category for WLF (using wood siding) and RPC structures

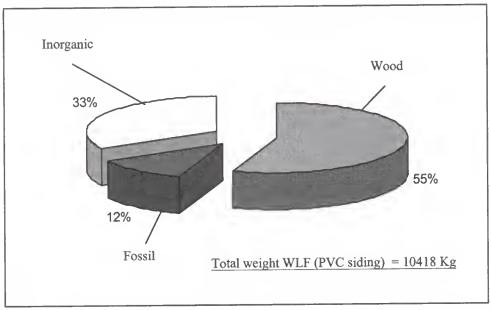


Figure 7.3 Summary results, composition by weigh% of wood light frame structure

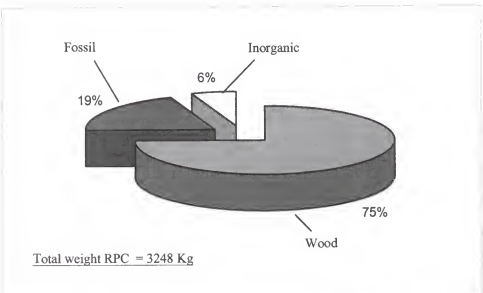


Figure 7.4 Summary results, composition by weigh% of RPC structure

CHAPTER 8
SUMMARY RESULTS & DISCUSSION

The objective of the research presented in this dissertation was to contribute to the development of construction technologies that address issues of adequate housing for all and the need for more sustainable human settlement. The emerging technology of rigidified pneumatic composite (RPC) was investigated as a mean to accomplish more sustainable construction technologies. A new material was proposed; developed, and evaluated that can be used in this technology. A synopsis of research findings is presented including a summary of research results. Following this, recommendations were made to direct future development in this area of research.

Summary Results

RPC, Some Theoretical Solutions

A framework was presented that can aid in the development of materials useful in RPC technology. This framework focused on the identification of systems that can be used to stiffen polymeric membranes. Systems proposed included methods in which; 1) molecular weight of a polymer is increased, 2) Cross-link density of an existing polymer is increased, 3) Chain rotational stiffness of an existing polymer is increased, 4) Inter molecular attraction of an existing polymer is increased, 5) Free volume of an existing polymer is decreased, and 6) Passive cooling techniques are applied. In addition to this, several means to control the stiffening process were also introduced. For systems that require no chemical cure, these included thermal cure, light cure, gas cure, and cure with liquid or aerosol. For systems requiring no chemical cure, this included the use of

mechanical energy and evaporation of plasticizer. The relative benefits and disadvantages of each were also described.

Semi-IPN Based on PVC and Reactive Plasticizer

A new material was developed based upon the above findings and examples found in the literature. The particular system was a semi-IPN based on PVC and a reactive plasticizer. Plasticized sheets of PVC were rigidified by polymerization of the reactive plasticizer upon exposure to UV-light. Samples were prepared and tested for tensile strength, modulus of elasticity, and glass transition temperature. Results indicated average tensile yield strengths of about 25 MPa, a modulus of elasticity of about 2.5 GPa (at 25 °C), and a glass transition temperature of about 50 °C. In addition to testing this matrix system, the performance of this matrix was also tested when applied to various reinforcing fabrics (cotton, glass, and Kevlar). It was found that these samples were highly an-isotropic. It was also found that when reinforcing thin polymeric membranes with fiber fabric, care must be given to select reinforcement systems for which fiber diameters are proportional to the overall thickness of the lamina.

Structural Analysis of an RPC Structure

A structural analysis was performed for an RPC structure in order to determine material properties needed to accomplish safe design. The structural analysis involved the analysis of a simple prismatic building composed of tubular beam and column elements. A hypothetical building-site, located in a tropical climate with open terrain topography and wind speeds as strong as 130 mph was selected to determine structural loads. SSTAN, a Simple Structural Analysis Program using finite elements for static load analysis of three-dimensional structural systems was used to analyze the RPC-structure. The outcome of this analysis was used to determine safe material properties using the allowable stress method. It was found that maximum tensile and compressive yield strengths of about 80MPa, a maximum allowable shear strength of 3.4 MPa, and a

modulus of elasticity of 8.5 GPa were needed to make the particular design safe. It was concluded that when carefully designed, these properties should be accomplishable with semi-IPN systems based on PVC and reactive plasticizer. Considering the assumptions that were made, it was also concluded that a more complex analysis including for example thermal effects, creep, concentrated loads, and an-isotropic material response are needed before a more conclusive recommendation could be made.

Life Cycle Cost of an RPC

In order to asses the economical performance of RPC structures, the life cycle cost for an RPC building was compared to the LCC of a similar building using a more conventional wood light frame (WLF) construction system. The scale of the structures compared was that of a prismatic building, 24feet wide, 48feet long, and 8 feet high. The assumed service life was 40 years. The analysis only included those cost components that were significantly different. It was found that the LCC of the RPC structure was about 35% less than the LCC of the WLF structure (or $30507 for the WLF structure and $19658 for the RPC structure). A cost breakdown was also provided for the RPC structure. It was suggested that the LCC for the RPC structure could be significantly reduced if 1) Lower cost RPC membranes can be developed, 2) different materials could be identified for the insulating filling and protective skin, and 3) the structural design was more optimized.

Environmental Considerations

An initial assessment of the environmental performance of RPC technology was performed by comparing the relative performance of an RPC structure to that of a wood light frame structure. The assumption was made that a system that uses comparable materials for construction will perform better environmentally when lesser quantities of these materials are used. The case study used to determine LCC was used for this purpose. Materials used in both systems were quantified and placed in categories of

materials coming from similar resource (wood, fossil, inorganic). The results of this analysis revealed significant differences between the two systems. First, the RPC structure was found to be extremely lightweight (3248 Kg) compared to the wood light frame structure (10424 Kg). Second, the RPC structure uses about two times less material that is derived from fossil resources relative to the WLF structure (630Kg compared to 1220 Kg). The RPC structure further used much less materials derived from trees. Results indicated that the use of RPC composite materials can provide significant environmental benefits. First, since comparable resources are used in lesser amounts (relative to the WLF structure), the environmental impacts of resource consumption will be less. Second, no wood is used as structural material in the RPC structure, hence no trees need to be cut for this purpose. Third, the use of fewer resources will also ease the waste management problem afterwards. In addition to this, RPC structures are also more homogeneous in composition facilitating the separation of wastes resulting in more convenient recycling of the materials. Finally, the RPC structure provides significant weight savings resulting in less energy use during transportation. It was also pointed out that both systems could be optimized from an environmental standpoint by simply selecting different system components.

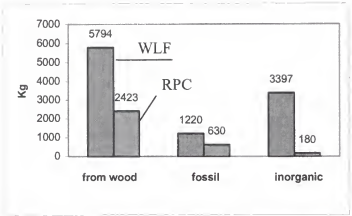


Figure 8.1 Composition in Kg for each category for WLF (using PVC siding) and RPC structures

Recommendations for Future Research

In light of sustainable development goals and issues of affordable housing, results of this research indicate that RPC structures have great potential in addressing some of the current needs. Successful implementation of this new technology however will require substantial additional research efforts, especially focusing on the following areas:

Cost of Ownership

A difference of 35% in cost of ownership is fairly significant. However considering the high risks involved with the implementation of this new technology, this difference may not be enough yet. In addition, a total initial cost of about $10937 for a 1200 SF house is still beyond the reach of many individuals or families living in less developed countries. As mentioned above, the LCC for the RPC structure could be significantly reduced if 1) lower cost RPC membranes can be developed, 2) different materials could be identified for the insulating filling and protective skin, and 3) the structural design was more optimized. The identification of lower cost membrane can include the examination of low cost fillers (such as $CaCO_3$), the use of lower cost reactive plasticizer, and the use of lower cost reinforcement. Identification of low cost substitutes for the protective skin and insulating filling are other major means to reduce overall cost. The use of agricultural waste materials can be examined as low cost insulating filling materials. The use of vegetation is a possible affordable way to protect the RPC structure against environmental degradation. Finally, optimization of structural design can reduce cost significantly. More detailed FEM analysis is therefore another major area for future research.

RPC Long Term Performance

The calculated LCC for the RPC structure assumed that the RPC structure was equally durable over a life span of 40 years when compared to the WLF structure. Although certain assumptions were made that can justify this, actual performance data

would provide much more confidence in these LCC results. The actual testing of RPC structure, either over long periods of time, or for example by means of accelerated weathering tests, is therefore another major area of research.

Environmental Performance

The environmental performance of RPC structures is perhaps the most attractive feature of this technology (and of fiber reinforced polymers in general). The same thoughts concerning long-term performance apply however. Ideally, RPC structures will be very durable. If not, then they should not require substantial financial and material resources for operation and maintenance. In absence of these requirements, the environmental promise of this technology might not be delivered. In addition to assessing the long-term performance, another major area of research will therefore be to identify means to increase long-term performance or to identify environmentally sound maintenance and repair practices. In addition to this, continued effort should be spent to identify and develop new materials that rely less on non-renewable resources and more on the utilization of renewable resources (such as for example agricultural by-products).

Indoor Air Quality

Fifty percent of new buildings today suffer from the so-called sick building syndrome caused for example by off-gassing of volatile organic compounds or VOC's [Roodmann and Lenssen, 1995]. These VOC's are composed of low molecular weight compounds that are present in most building materials and that diffuse to the material surface over prolonged periods of time. Distribution of these compounds into the indoor air may in turn adversely effect human health. When developing RPC materials therefore, it is of importance to select material components that are safe in this respect (such as products that are approved for prolonged contact with food). Identification of such materials is therefore another major area for future research.

Agenda 21 and the Habitat Agenda

The aim of this dissertation was to contribute to the development of architectural technologies that address issues of adequate housing for all and the need for more sustainable human settlements. It is clear that this objective is very ambitious and that in reality no technological development within itself can address all of the complex issues involved. Building upon the recommendations made by agenda 21 and the habitat agenda, current strategies tend to focus on establishing policies that support and reinforce locally established practices. It is often proclaimed that little need exist for new technologies to address this overwhelming problem; instead emphasis is placed on the rediscovery of vernacular construction technologies. These efforts build upon the argument that vernacular technologies have proven to be sustainable within the social, economical, and environmental context that is locally prevailing. However, within a world that is changing at rapid pace, local contexts are changing as well. Locally available resources may have been exhausted, economical infrastructures disappeared, and social models may have been changed. Therefore, vernacular construction technologies may not always remain sustainable within a changing local context. In a world were technological developments occur at a rapid pace, the interface between old and new becomes of primary concern and interest. This is especially true considering the current gap that exists between the less and more industrialized areas of the world. With regard to construction technologies, those that are alien to local conditions often have failed to sustain themselves. The development of advanced technologies that accommodate local conditions within a global context of sustainable development may therefore be more successful. It is within this context that RPC technology should be placed. The objective of this study was in part to develop advanced technologies that can be delivered in a simple way using existing infrastructures and skills. In light of the priorities set forward by

Agenda 21 and the Habitat Agenda, RPC technology specifically contributes to the following areas:

1) Emphasis is placed by both agendas to develop construction technologies that rely on locally available skills and infrastructures. RPC technology lends itself to both large-scale and small-scale product delivery. In large-scale delivery, RPC structures are pre-manufactured in bulk and delivered on-site ready for inflation. In small-scale delivery, RPC membrane materials are manufactured by local industries and structures are pre-manufactured by local small businesses using existing skills and infrastructures. Both large scale and small scale delivery is possible since RPC technology largely uses the same skills that are used by the textile industry. Since these skills are well established and developed worldwide, especially in the developing world, implementation will require little investment in both skills and infrastructure. This ability is fully in line with the recommendations made in agenda 21 and the Habitat agenda in which the development of small-scale local building industries are encouraged. Both agendas also promote the construction of self-build housing. Since the skills needed to make RPC structures are well established, this should also be possible.

2) Strong emphasis is also placed by both agendas to develop construction technologies that are environmentally sound and affordable; use locally available building materials and resources; substitute for or optimise the use of non-renewable resources; reduce polluting effects, paying special attention to recycling, reuse of waste materials and increased reforestation; apply low-energy, environmentally sound and safe manufacturing technologies; use safe industrial and agricultural waste products and other types of low-energy and recycled building materials in construction. RPC technology is also fully in line with these recommendations considering the results and recommendations presented above.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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